Environmental Product Development Combining the Life Cycle Perspective with Chemical Hazard Information

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Publication date:
2011

Document Version
Early version, also known as pre-print

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2011

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Forskningsgruppe/Research group: Environmental Assessment & Governance

The PhD dissertation is handed in for assessment to the
Faculty of Engineering and Science, Aalborg University
Ph.d.-afhandling indleveret til bedømmelse ved Det Teknisk-Naturvidenskabelige
Fakultet, Aalborg Universitet

Titel/Title: Environmental Product Development Combining the Life Cycle Perspective with Chemical Hazard Information.

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Projektperiode/Project period: 2007-2011

PhD vejleder/PhD supervisor: Per Christensen and Ole Jørgen Hanssen

Collaborating partners: Ostfold Research, Jotun A/S, HÅG as, The Research Council of Norway and The Confederation of Norwegian Enterprise (NHO)

Oplagstal /Copies: 40

ISBN: 978-87-91830-53-2

English Summary

Concerns regarding the short- and long-term detrimental effects of chemicals on human health and ecosystems have made the minimisation of chemical hazards a vitally important issue. If sustainable development is to be achieved, environmental efficient products (and product life cycles) are essential. Many life cycle assessments of product systems are performed without the inclusion of toxicity data and indicators. Ecodesign processes for products are often based upon just one, or very few, environmental indicators. Regulatory issues are sometimes addressed in an *ad hoc* fashion, often late in the design or redesign process. This thesis concerns marrying the life cycle perspective with chemical hazard information, in order to advance the practice of environmental product development, and hence takes further steps towards sustainable development.

The need to consider the full value chain for the life cycle of products meant that systems theory and systems engineering principles were important in this work. Life cycle assessment methodology was important for assessing environmental impacts for case products. The new European regulation for chemicals (REACH) provided the main driver for regulatory considerations – understanding and linking REACH to life cycle impact assessment (LCIA) was a central theme of the work. The research encompassed regulatory toxicology and its links to the REACH regulation and LCIA.

The research was based on empirical data for products and scenarios of interest to partner companies (in coatings manufacture and in seating production). Two product development tools have been developed. These tools were a result of collaborative processes, thus ensuring their practical usefulness and their direct applicability to the partners' strategic product development processes. These case studies and company collaboration led to the development of a model that clearly links the tools developed to the Ecodesign process. The model for this interactive, iterative use of these tools for decision support, from early stage in the design process, is widely applicable for companies across industries. The inclusion of these tools in decision support for Ecodesign will facilitate the integration of a life cycle perspective and chemical hazard information within environmental product development.

Resume

Minimering af kemiske farer er et meget vigtigt spørgsmål i forhold til kemikaliers skadelige indvirkninger på menneskers sundhed og økosystemer på både kort og lang sigt. Hvis en bæredygtig udvikling skal opnås, er miljøeffektive produkter (og produkters livscykluser) af afgørende betydning. Mange livcyklusvurderinger af produktsystemer er foretaget uden at inddrage toksicitetsdata og indikatorer. Ecodesign af produkter er ofte baseret på kun én eller meget få miljøindikatorer. Hensyn til lovkrav bliver nogle gange behandlet ad hoc, ofte sent i design- eller redesignprocessen. Denne afhandling handler om at koble livscyklusperspektivet med information om fareoplysninger for kemikalier, for at fremme en miljørigtig produktudvikling, og dermed tage yderligere skridt mod en bæredygtig udvikling.

Systemteori og systemudviklingsprincipper har været vigtige i arbejdet med at vurdere hele værdikæden af produkters livscyklus. Livscyklusmetoden har været vigtig for at vurdere case-produkternes miljøpåvirkninger. Den nye EU-forordningen for kemikalier (REACH) har været den vigtigste drivkraft i forhold til myndighedernes regelsæt. Et centralt tema i arbejdet har været at forstå og koble REACH til livscyklusvurdering (LCIA). Forskningen omfattede regulatorisk toksikologi og hvordan dette kan knyttes til REACH-forordningen og LCIA.

Forskningen var baseret på empiriske data for produkter, og relevante scenarier for partnervirksomshederne (producenter af maling og møbler). Der var udviklet to produktudviklingsværktøjer i samarbejde med virksomhederne. Dette sikret at værktøjerne var praktisk anvendelige og kunne bruges direkte i partnernes strategiske produktudvikling. Casestudierne og samarbejdet med virksomhederne førte til udvikling af en model, der gav en klar forbindelse mellem de udviklede værktøj og Ecodesign. Modellen er en interaktiv, iterativ brug af værktøjerne som beslutningsstøtte allerede tidligt i designprocessen, og den er i høj grad anvendelig for virksomheder på tværs af brancher. Brugen af disse værktøjerne vil forenkle en integrering af et livscyklusperspektiv og information fra fareoplysninger for kemikalier i en Ecodesign proces.

Acknowledgements

The close collaboration Ostfold Research has with industry, and the experience and insight that I have gained in working with LCA here, have been essential for this thesis. I would like to thank Ostfold Research for giving me this opportunity, and all the support that I have had from the management and my colleagues here. I would like to thank the Research Council of Norway (BIA programme), the Confederation of Norwegian Enterprise (through the Workplace Environment Fund), Jotun A/S and HÅG as for their financial support and contributions to the empirical work. I would also like to thank Aalborg University and my supervisors, Per Christensen and Ole Jørgen Hanssen, for their advice and guidance during this process. Ole Jørgen, you have been my co-supervisor. I have jokingly described us as occupying two different orbits that intersect on occasion. These interceptions have always been valuable. Thank you.

I would also like to thank you, Ed, for proof-reading most of the supporting papers for this thesis. You have been a big help.

John, your humour and unlimited support have been invaluable throughout the process of writing this thesis and many of the supporting papers, thank you so much.

To my dear colleagues, you have been a wonderful combination of cheerleaders (heiagjeng), and technical and moral support. You have been a kind of extended family for me these last (almost) fourteen years – wow, has it really been that long? Hanne, thank you for your help with translation. Andreas, I am also very grateful for your valuable comments on drafts of this thesis. Thank you.

To my dear sisters, friends and support network – thanks for all your help and support during this time, and I am so looking forward to more fun and enjoyment in your company.

Jens - you have been the most important part of my life during these PhD years. You have been born and grown so much during the same time as this thesis. This thesis' development has reached its limit, but you are just beginning yours. I'm so enjoying being a part of that. Thank you for keeping me grounded. You remind me of what is really important in life, like empirical studies of whether Thomas is tougher than your monster truck, or whether your bucket full of dinosaurs can roar so loud that they scare The Gruffalo. You are such a joy to be with and such a breath of fresh air when I've been buried in work for too long.

Contents

List of Supporting Papers

Paper I: Askham C. (2011) REACH and LCA – Methodological Approaches and Challenges. Submitted for publication. Int. J. Life Cycle Assess.

Paper II: Askham C. (2011) Environmental Product Development: Replacement of an Epoxy-Based Coating by a Polyester-Based Coating. Int. J. Life Cycle Assess. http://dx.doi.org/10.1007/s11367-011-0302-x.

Paper III: Askham C, Gade AL, Hanssen OJ (2011) Combining REACH, Environmental and Economic Performance Indicators for Strategic Sustainable Product Development. Submitted for publication. J. Cleaner Production.

Paper IV: Askham C, Gade AL, Hanssen OJ (2011) Combining Chemical Risk Phrase Information with a Life Cycle Assessment Approach for Product Development. Submitted for publication. Int. J. Life Cycle Assess.

Paper V: Askham C, Hanssen OJ, Gade AL, Christensen P (2011) Strategy Tool Trial for Office Furniture, Submitted for publication. Int. J. Life Cycle Assess.

1. Introduction

A wide body of research documents evidence for human impacts on the environment and our ability to degrade the ecosystems we depend upon. Visser (2009) presents a summary of global reporting and tracking that documents these issues, stating: "As our knowledge of the state of the planet has improved, denial is no longer a credible position. We now have evidence of the scale of our human impacts the seriousness of our predicament and the urgency for action". Sustainable development is a concept that has been hailed as the solution to the problem of over consumption of the world's resources and pollution of our environment. The World Commission on Environment and Development and their report defined the concept in a way that captured wide interest and acceptance and has remained relevant. Their definition of sustainable development was: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Sustainable development encompasses social, economic and environmental dimensions; it aims to preserve the environment whilst securing economic growth (Brundtland et al. 1987). Companies and product development therefore play important roles in ensuring sustainable development.

There are several examples in modern history where product development has been driven by a specific driver or indicator and led to unexpected consequences. Well known examples are the unexpected effects of pesticides and biocides in focus in the 1960s (Carson 1962) and brominated flame retardants. These flame retardants are in wide use in society today, in electronics, furniture and other applications. They are useful chemicals, helping to inhibit the spread of fire, and are thus meant to save lives. However, in the long term they have been seen to build up in human body fat and in the body fat of other mammals. They are persistent, bioaccumulative and toxic, thus they have long term effects on the health and ability of organisms to reproduce, affecting biodiversity (Macgregor et al. 2010, Brown et al. 2006, Norén and Meironyté 2000). Such unintended consequences might have been avoided had multiple drivers been taken into account during product development. If long-term toxicity aspects had also been considered, it is possible other product choices may have been made. It is unlikely that this problem can be entirely eliminated, but it is possible to be optimistic that designers and decision-makers can be presented with several indicators at once. This would enable them to be aware of complex trade-offs between different health and environmental aspects in the product development process and facilitate contemplation of the potential outcomes of the decisions to be made.

The United Nations Environment Programme (UNEP) has identified six priority areas defining their focus on the environmental challenges of the 21st century: climate change, harmful substances, resource efficiency, disasters and conflicts, ecosystem management and environmental governance (UNEP 2011). Sustainable product development is an approach business can adapt in an attempt to minimise human impacts on the environment, while sustaining or increasing economic activity. Klöpffer (2003) and Hanssen (1997) give examples of how sustainable product development can be enhanced and supported by the use of life-cycle based methods. Brezet et al. (1997) present ecodesign as a promising approach to achieving sustainable production and consumption. The importance of hazardous substances and their effects on the sustainability of ecosystems makes it vital to provide practical tools and approaches that will meet stakeholder needs across value chains. Environmental product development combining the life cycle perspective with chemical hazard information clearly touches on the first three of UNEP's priority areas (climate change, harmful substances and resource efficiency). Visser (2009) also identifies industry initiatives as important for sustainable development, with “collaboration is better than competition”. He states that sector-based responses to sustainability, if they adopt a stakeholder-driven approach, are perhaps the best way to bring about substantive change. The work has been stakeholder driven; answering specific needs of stake-holders concerning regulations and sustainable product development. However, the case studies this thesis work is based upon encompass supply chains relevant for coatings and furniture producers. They represent a value-chain approach, which is a cross-sector approach.

Growing concern about the negative long-term effects of chemicals on humans and eco-systems led to a desire for early warning and prevention of these unforeseen effects, and the use of the precautionary principle as the basis for chemicals regulation arose (Løkke 2004). Historical developments in legislation and international cooperation leading to the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation are well described in Løkke (2004) and Van Leeuwen and Vermeire (2007). Van Leeuwen and Vermeire (2007) describe the precautionary principle as “a cornerstone of the REACH legislation”. The Organisation for Economic Co-operation and Development (OECD) took a leading role in developing international consensus on good laboratory practice and testing procedures. This work from the 1980s was also an important basis for the division of labour and schedules of tests that is reflected in the REACH regulation today. Developments in occupational health regulations internationally were also important for the development of REACH, in order to minimise the adverse effects on the health of workers producing and using chemicals (Løkke 2004).

REACH[1] is closely connected to UNEP priorities on harmful substances. This is a regulatory response to the challenge of minimising the effects of hazardous substances on humans and ecosystems. The assessments required by companies in response to REACH are aimed at addressing concerns about impacts on human health and ecosystems from hazardous substances in our society.

The new European REACH regulations entered into force on 1st June 2007 to streamline and improve the EU’s former legislative framework on chemicals. REACH places the responsibility on industry to carry out chemical safety assessments and manage the risks that chemicals may pose to human health and the environment. The aims of REACH are: to improve the protection of human health and the environment from the risks that can be posed by chemicals; to enhance the competitiveness of the EU chemicals industry, a key sector for the economy of the EU; to promote alternative methods for the assessment of hazards of substances; and to ensure the free circulation of substances in the internal market of the EU (ECHA 2011, Van Leeuwen and Vermeire 2007).

The recent Official Norwegian Report “A Norway without Hazardous Substances” (Hylland et al. 2010) defines hazardous substances as substances or groups of substances that are a serious threat to human health and/or the environment. They are described as substances that are toxic, slow to biodegrade (persistent) and accumulate in organisms; other substances are classed as hazardous because they cause detrimental effects on human health, or ecosystems at low concentrations and affect important biological processes. Hylland et al. (2010) document that sources of hazardous substances being emitted to the Norwegian environment have changed in

[1] EU regulation for Registration, Evaluation, Authorisation and Restriction of Chemicals (Commission of the European Communities 2007)

the last decades. Large, industrial point sources are no longer the main challenge (although there are still some of these), as these have been largely replaced by diffuse sources. Norway, like many other countries in Europe, has experienced a reduction in on-shore heavy industry and an increase in the import of products. Leaks of hazardous substances from historical sources via contaminated land, sediment and landfills are still a large problem and a reminder that substances that are persistent must be strictly regulated and avoided. However, long-distance transport of hazardous substances is now a significant source for Norwegian levels of hazardous substances. Hylland et al. (2010) stress that persistent and bioaccumulative substances are a global problem, both long-distance transport of these substances in the global eco-system and import of products containing hazardous substances mean that Norway must be active internationally in order to reduce the threats from these substances. Erik Solheim (Norway's Minister of the Environment and International Development) said "I want Norway to be a driving force for stricter environmental regulations internationally. The proposed prohibitions send an important signal that Norway takes the challenge from hazardous substances in consumer products seriously" (Norwegian Ministry of the Environment 2010). These political signals are a result of the trends documented in Hylland et al. (2010), including the globalisation of the production and transport of consumer goods to markets. Thus it is clearly important to consider the entire product life cycle (including resource extraction, raw materials production and disposal - all potentially giving rise to large point sources) as an important approach to understanding and reducing the sources of hazardous substances in the environment.

Life cycle assessment (LCA) is an established internationally standardised method for assessing the life cycle environmental impacts of products, from cradle-to-grave (ISO 14044 2006, European Commission 2010a). It takes into account a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to final disposal. The LCA approach has the capability to avoid unwanted "shifting of burdens", where the environmental impact is reduced at one point in the life cycle, but increased at another point or where one environmental impact is reduced where other environmental impacts are increased (European Commission 2010a). The European Commission Joint Research Centre describes LCA as a vital and powerful decision support tool, contributing to help make consumption and production more sustainable effectively and efficiently (European Commission 2010a). LCA is used to assess product value chains and product sustainability. It is a method that is often used to document environmental performance and assess product system improvements (Hanssen 1997, Baumann et al. 2004). The importance of a life cycle approach in order to aid progression towards sustainable consumption and production is also highlighted by the existence and activities of the European Commission Joint Research Centre's Institute for the Environment and Sustainability and their Life Cycle Thinking and Assessment activities (European Commission 2011). The project "Life cycle based indicators" describes these as essential to monitor progress towards sustainable consumption and production, with particular focus on the decoupling of environmental impacts from economic growth.

Results from LCA studies used for product or system improvements have shown that it is not always the case that all impacts can be reduced by a given improvement option (Modahl et al. 2008, Modahl et al. 2009, WRAP 2006, Hertwich et al. 2008). There can be trade-offs between environmental impacts; for example reducing global warming potential at the expense of increasing other environmental impacts such as acidification or toxic impacts (Wenzel et al. 2008, Høibye et al. 2008). These potential trade-offs highlight the need to consider product and product system changes from a holistic and functional perspective; if this need is ignored, then purported improvements may have unintended and even counterproductive consequences.

It is common that LCAs and environmental product declarations (EPDs) based on LCA do not include human health, or ecotoxicity impacts (Abrahamsen et al. 2008). There are, however, attempts at remedying this. SETAC has for instance recently established an initiative to develop a scientifically based methodology for evaluating chemical footprint, which should lead to the development of calculation guidelines for the purpose. Their vision is that chemical footprint will be as important as carbon footprint and water footprint for products in the future (IVL 2011, SETAC 2011).

This thesis contributes to developing LCA with regard to the inclusion of hazardous substances through connecting information from LCA with information related to REACH. Furthermore, it aims at making the resulting information operational for companies in product development. The thesis is constructed in four main parts. The first part consists of the motivation for the research, definition of the problem in the form of research questions that are explored in the work presented, and the research approach. The fields of research and theory drawn upon are expanded in more depth in the chapter Theoretical Basis, which is the second main part of this thesis document. The third main part of the thesis is an illustrative case study, where a fictional company is used as an example of the tools developed during this PhD work and presented in three of the supporting papers. The final, concluding part of the thesis consists of Conclusions and Perspectives for Future Research.

1.1 Problem Definition

The thesis statement that this PhD work is based on is:
"*It is possible to combine information from REACH with the LCA approach to develop more environmentally optimal products.*"
Scandinavians often use the expression "the red thread" to describe a theme that runs through a piece of work, such as a PhD. This thesis statement can be thought of as the red thread through this work.

Research Questions central to this study:

- What are the similarities and differences between the REACH and Life Cycle Assessment (LCA) approaches, and how can synergies between these two approaches be exploited to achieve environmental improvements in a holistic perspective?
- Will the REACH approach (with a hazard risk focus) and the product functionality focus that is central to LCA be at odds with one another, resulting in different priorities for product development?
- Can REACH and LCA approaches to product development be combined to make strategic product development tools that are of use to companies?
- How can REACH contribute to providing data to strengthen life cycle impact assessment models?

Answering the first research question was important for acquiring detailed knowledge about these two approaches, hence identifying potential synergies and opportunities for the environmental improvement of products. The issue of potential conflict between the two approaches was important for establishing whether REACH could entail a danger of sub-optimisation in a product life cycle perspective. The final two research questions concerned issues at a more operational level. They each address practical issues for including the two approaches in product development, as well as contributing to better inclusion of chemical hazard information in LCA. Chapter 1.3 describes how the research questions are addressed in the supporting papers.

1.2 Research Approach

The empirical basis for this PhD centered around products and life cycles relevant for the two partner companies in the Innochem project (Jotun A/S, the coatings producer and HÅG as, the seating producer). Both companies were also concerned about the challenges and documentation burdens that have arisen as a result of REACH, wishing to be proactive in their approach to the new regulation. These drivers led to a comparison (and ultimately combination) of two approaches to environmental improvements: REACH and life cycle assessment (LCA). LCA is a systems analysis method suitable for analysing product life cycles from cradle-to-grave, and comparative analysis of environmental improvement options (see Chapter 2.2). Whilst the intent of both approaches is to drive the reduction of environmental impacts in society, each approach has a markedly different focus. This PhD project attempted to inform how (the partner) companies might optimise their environmental performance in the context of these drivers. This included: highlighting potential sources of confusion or contradiction between the drivers, evaluating potential adverse effects of response to the drivers, and identifying and exploiting synergies between them. It was therefore natural to investigate how different chemicals are treated in REACH and in LCA methodology, and use real cases from industry to test, compare and integrate the two approaches.

Askham (2011a, Paper I) provides an in-depth look at the similarities and differences between REACH and LCA. The REACH information in this paper is mainly based on the regulation, guidance documents and regulatory toxicology principles (Commission of the European Communities 2007, ECHA 2011, Van Leeuwen et al 2007). Similarly the LCA methodology and information that the paper is based on comes from ISO standards, guidance documents and text books and papers about LCA (for example ISO 14044 2006, European Commission 2010a, Baumann et al. 2004, Reap et al. 2008). The main research question addressed in this paper was: "*What are the similarities and differences between the REACH and Life Cycle Assessment (LCA) approaches, and how can synergies between these two approaches be exploited to achieve environmental improvements in a holistic perspective?*" The research question: "*How can REACH contribute to providing data to strengthen life cycle impact assessment models?*" was also considered. This work provides information about synergies and possible conflicts between the consequences of implementing REACH and LCA. It identifies both opportunities and potential obstacles in environmental performance improvements in response to these drivers.

The work to this point indicated that potential conflicts between product development drivers, and hence the need for trade-offs between them, was a considerable concern for industrial product development. Askham (2011b, Paper II) explores this issue by studying a potential compromise between environmental performance improvement and occupational health issues. The work highlights the practical implementation of LCA within product development and integrates this with qualitative analysis of occupational hazard issues. In this case the two factors were found not to be in significant conflict, nonetheless the work indicates how such conflicts might be identified and resolved. The specific research question for this work was: "*Will the REACH approach (with a* *hazard risk focus) and the product functionality focus that is central to LCA be at odds with one another, resulting in different priorities for product development?*"

The work then builds upon these developments in theoretical and methodological understanding, turning to the exploitation of synergies between REACH and LCA for environmental performance improvement, and ultimately competitive market advantage as a consequence. Three papers - Askham et al. (2011a, Paper III), Askham et al. (2011b, Paper IV) and Askham et al. (2011c, Paper V) – all address aspects of the research question: "*Can REACH and LCA approaches to product development be combined to make strategic product development tools that are of use to companies?*" The first of these papers highlights work with a producer of substances in mixtures (Jotun A/S). The research enables product screening, benchmarking and portfolio development - by combining indicators for REACH Complexity, health and environmental risk, and environmental performance, with financial market data. The REACH complexity and health and environmental risk indicators all have a basis in regulatory toxicology (see Chapter 2.3). The strategy matrix approach is closely linked to the Eco-portfolio matrix presented by Brezet et al. (1997) (see Chapter 2.5). The Strategy Tool developed facilitates the understanding of complex trade-offs between different health and environmental aspects, and also informs broader strategic decision-making (for example the concentration of marketing efforts). The Strategy Tool was deployed in practice at specific "gates" (or milestones) in the company's product development processes. Working closely with relevant teams across departments to develop the Strategy Tool, ensured the tool's practical usefulness, the availability of relevant data and the applicability of the results to the company's product development processes.

The essential methodological developments leading to the Strategy Tool were more fully exploited in the next stage of the work. Askham et al (2011c) extends the work into the office furniture sector (with HÅG as). This implied a broader range of potentially relevant environmental indicators than for the previous substances-in-mixtures work with Jotun A/S. The work addresses an additional research question: "Will the life cycle approach result in different priorities for product development than a purely hazardous risk information approach?" The potential for conflict and the need for trade-off between REACH and environmental factors was considerably more prominent in this work than previously. The empirical data source for the LCA-based environmental information was the environmental product declarations (EPDs) for eleven of HÅG's chair products - data for seven different environmental indicators was available from these EPDs. The work showed how analysis spanning multiple environmental indicators could be condensed by identifying correlations between them. The case study provides a very clear example of how product designers have to consider multiple aspects in parallel and the Strategy Tool's usefulness for this purpose; the furniture producer gained useful product development insight.

The LCA approach that was used in Paper II and Paper V, can be described as retrospective (Tillmann 2000, Ekvall et al. 2005), or attributional (European Commission 2010a). This is appropriate for Type III Environmental Declarations and Ecodesign projects (EPDs) (Baumann and Tillmann 2004, European Commission 2010a). The term attributional is applied to LCAs performed for systems where the data used are historical. The aim of the case study in Paper II was to analyse whether the change from the epoxy-based coating to the polyester-based coating had the desired improvement effect. Thus, it is a typical case where the attributional approach (Type A situation) is appropriate (European Commission 2010a).

The strategy Tool was used to identify products that need further development or redesign (Paper III, Paper V). This tool gave a clear indication of whether the redesign was required based on LCA indicators, chemical hazard risk, or both. A new tool (the Screening Tree Tool) was developed in an LCA software package (SimaPro 7.3), combining the LCA approach with chemical hazard information (human health and environmental hazard) and exposure pathways. This enabled the product designers to efficiently identify which chemicals and raw materials pose significant hazards and the important exposure pathways. This tool can also be used as a screening tool for new designs/product formulations. Two Research questions are addressed in Paper IV: "*Is it possible to combine REACH hazardous risk information with LCA methodology in product development?*" and "*Will the life cycle approach result in different priorities for product development than a purely hazardous risk information approach?*" These research questions and the work presented in Askham et al. (2011b) also contribute to answering the research question: "*Can REACH and LCA approaches to product development be combined to make strategic product development tools that are of use to companies?*" This last research question is not explicitly stated in the paper, but the illustrative case study (see 3 Jenson A/S: An Illustrative Case Study) will make this link clear.

The illustrative case study in this thesis will show the tools developed during the PhD work and how a company, wishing to use them in product development and company strategy could proceed. This case study and the supporting papers are used to answer the central research questions for this thesis.

1.3 The Case

The requirements of REACH impose a large burden of documentation on industry; this was an important driver for the Norwegian companies involved in the Innochem[2] project (Hanssen 2010). The Innochem project aim was to turn new regulations for chemicals into a promoter of innovation instead of being a threat to research and development (R&D), innovation and production of chemicals in Norway and Europe. Innochem is a collaborative project involving companies (Jotun A/S and HÅG as) and research institutions (Ostfold Research, NIVA, UiO, NTNU and Aalborg University). It is financed by the Research Council of Norway (BIA programme, Brenna 2010), the Confederation of Norwegian Enterprise through the Workplace Environment Fund and participating companies. The PhD has been performed in connection with the Innochem project. Jotun is a coatings production company and HÅG is part of Scandinavian Business Seating, producing chairs for the office and conference environment.

The two companies involved in the work presented in this thesis (Jotun and HÅG) have allowed the Innochem project team to gain insight into the processes and structures involved in each of their design and innovation systems. These two companies have recognised the importance and value of good organisation and the smooth integration of environmental requirements into the design process (Behrendt et al. 1997). The development and use of the Strategy Tool and the Screening Tree Tool (Askham et al. 2011a, Askham et al. 2011b, Askham et al. 2011c) are examples of how this necessary interdisciplinary and interdepartmental focus has been a success and resulted in the integration of the tools into specific design milestones in the companies involved. Simchi-Levi

[2] Innovations in Response to New Regulations of Conventional Materials in a Life Cycle, Functional and Holistic Perspective

et al. (2003) describes strategic alliances (Chapter 6) as typically multifaceted, goal-oriented, long-term partnerships in which both risks and rewards are shared. The partnership between these two participating companies is this kind of strategic alliance. Both derive benefit from working together to achieve better solutions for their customers. They are not competitors, Jotun is a supplier to HÅG and therefore has a vested interest in continuing sales to HÅG and aiding HÅGs work to document and improve the environmental performance of their products.

The REACH regulation was adopted by the EU in December 2006, and requires companies importing or producing chemicals (>1 tonnes/year) in the EU and EEA regions to register these chemicals with the EU's Chemicals Agency (ECHA). The requirements of REACH are relevant for both individual substances and substances in mixtures (for example paint), although the registration demand is for substances only. REACH requires companies to register the substance's identity, classification and labelling, test results and propose further tests for the substance, exposure potential to humans and different environmental compartments, and recommendations for safe use. The requirements for REACH increase with quantities of chemicals imported, or produced. Quantities greater than 10 tonnes/year/producer or importer mean that a risk assessment ("Chemical Safety Report", CSR) is required for the substance. If a chemicals company does not comply with REACH, it cannot sell the particular products in the markets of the European Union or the European Economic Area (Commission of the European Communities 2007). Figure 4.4 shows the overall process related to information requirements and chemicals safety assessment under REACH (ECHA 2010).

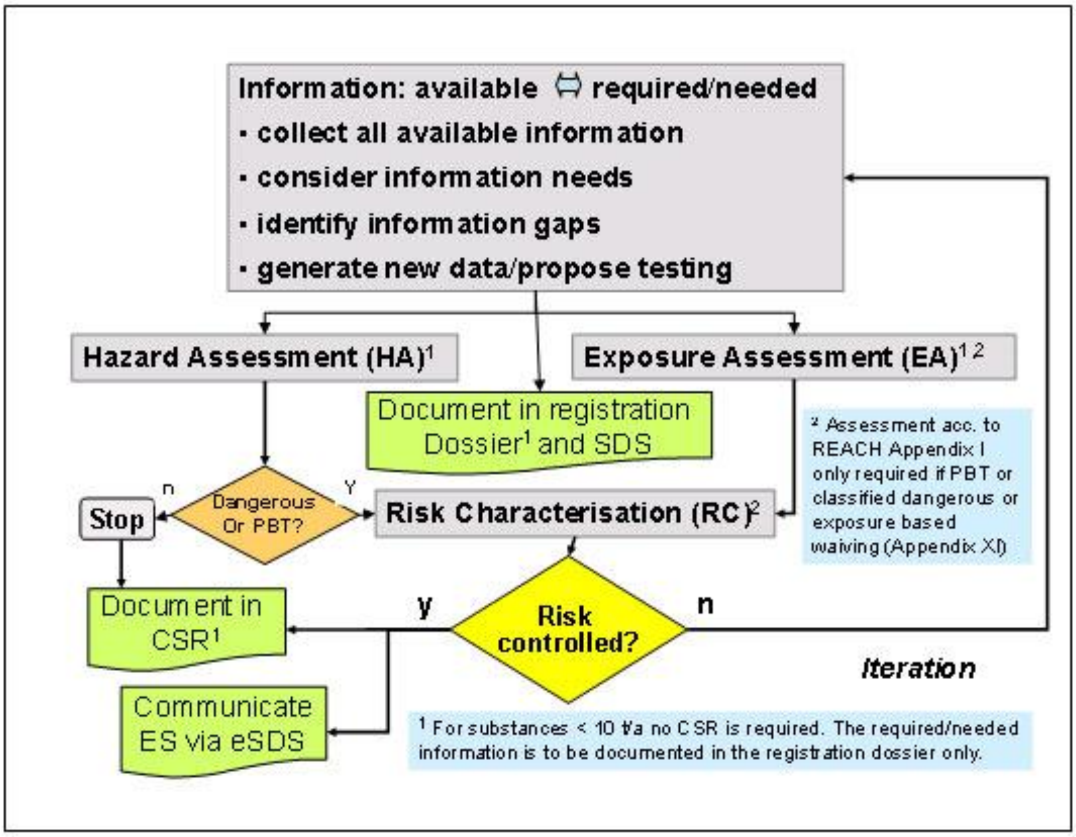

Figure 1.1 The overall process related to information requirements and chemicals safety assessment under REACH (ECHA 2010)[3]

[3] Abbreviations used in this figure: SDS stands for safety data sheets; PBT stands for persistent, bioaccumulative and toxic; CSR stands for chemical safety report; ES stands for exposure scenarios and eSDS stands for extended safety data sheet.

At the present time REACH requires that health and environmental risks associated with substances in mixtures are expressed as risk phrases (R-phrases) in line with international hazard labelling standards (ECHA 2008a) and European hazard labelling directives (Council Directive 67/548/EEC, Directive 1999/45/EC). It should be noted that R-phrases will be replaced by a new system defined in the CLP regulation, which has been adopted for pure substances on 1st December 2010 and will be adopted for substances in mixtures by 1st December 2015 (CLP regulation, Commission of the European Communities 2008). CLP uses hazard phrases (H-phrases), rather than R-phrases, introducing the new EU system for classifying and labelling chemicals, based on the United Nations' Globally Harmonised System (UN GHS 2005). ECHA (2009) describes the links between CLP and REACH as follows: "Many provisions of CLP are closely linked to provisions under Regulation 1907/2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) ..." REACH links are also noted in text boxes in relevant sections throughout the guidance (ECHA 2009). These links mean that hazard labels required for CLP are also considered a link to REACH. The responsibility to assess risks and hazards of substances is given to industry in the REACH regulation ("the natural or legal persons that manufacture or import substances") (Commission of the European Communities 2007). Risk and hazard information forms the scientific basis for labelling to be included in safety data sheets for substances and mixtures; both are again linked to CLP and to REACH.

2. Theoretical Basis

The progression of this theory chapter arises from the theme for the thesis, exploring the possibility of combining information from REACH with the LCA approach to develop more environmentally optimal products. Sustainable product development requires knowledge of the whole value chain or product system –this means that a systems engineering perspective is important. Systems theory and systems analysis are the starting points for this chapter. The chapter then addresses regulatory toxicology; knowledge of this is vital for understanding REACH and the possible synergies between REACH and LCA. LCA is a method based on systems theory and systems engineering principles (Hanssen 1997). Chapter 2.3 addresses the links between LCA and regulatory toxicology. Life cycle impact assessment (LCIA) methods are shown to build on the scientific knowledge and principles of regulatory toxicology. The final part of this chapter addresses Ecodesign and company approaches to strategic and sustainable product development.

2.1 Systems Theory and Systems Analysis

Systems theory is described by Hanssen (1997) as the scientific basis for modelling and design of product systems, as an example of complex networks for operation units with open relations to the external environment. A system is a thing built from many other things, or components for a common purpose (Oliver et al. 1997). Asbjørnsen (1992) provides the following general definition: “a system is a structured assemblage of elements and subsystems, which interact through interfaces. The interaction occurs between system elements and between the system and its environment. The elements and their interactions constitute a total system, which satisfies functional, operational and physical characteristics, as defined by the user and customer needs and requirements, over a defined total system life cycle of the system existence, including the life cycle of bringing the system into existence”. The systems engineering (SE) process can be described as the process of bringing a system into being including project planning, design, construction, and production.

Life cycle assessment (see 2.3) is described by Baumann and Tillman (2004) as an environmental systems analysis tool. Other examples of systems analysis tools given are Environmental Impact Assessment (EIA), Ecological Risk Assessment (ERA), Material Flow Analysis (MFA) and Cost Benefit Analysis (CBA). The life cycle inventory part of LCA focuses upon technical systems. Baumann and Tillman (2004) describe technical systems as managed and controlled by social systems and existing to supply people (social systems) with products and services. In this system view, technical systems use resources (from natural systems) and emit pollution and wastes to natural systems. Natural systems are affected by the pollutants and waste emitted. Social systems determine to what extent the changes in natural systems are interpreted as problems. The weighting step in LCA reflects the values and preferences within social systems. Baumann and Tillman state that since LCA models all three systems [technical, social and natural], it is necessarily multi-disciplinary.

Hanssen (1997) also describes Life Cycle Assessment as a method which is based on systems theory and SE principles. LCA follows the “Material Life Cycle” shown in Figure 2.1 and as such requires companies to address activities outside of their control and outside of their traditional responsibilities (Rex and Baumann 2008).

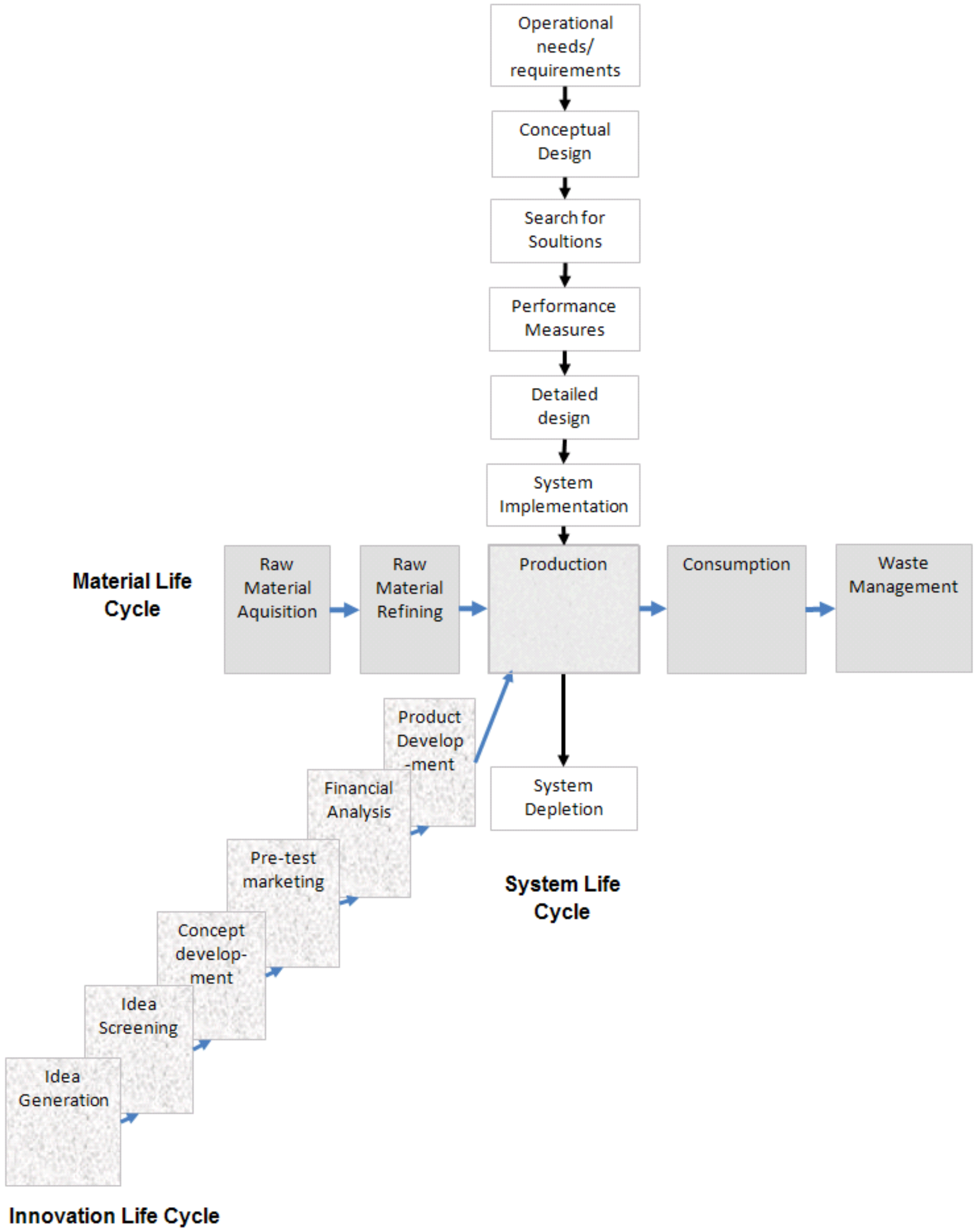

Figure 2.1: Interconnection between Systems Engineering (SE), Product Development and Innovation (PDI) and LCA (Material Life Cycle) models (Hanssen 1993)

A product's life cycle (often regarded as synonymous with its *supply* or *value chain*) typically defines the "system" as viewed by LCA practitioners and product designers. This is represented by the horizontal life cycle ("material life cycle") shown in Figure 2.1. Systems engineers are usually concerned with the system life cycle and the processes needed to bring the production system into being (vertical life cycle in Figure 2.1). To the systems engineer, probability, uncertainty, and risk are major elements in life cycle analysis in addition to life cycle costs and environmental impacts associated with that product's supply chain ("product system") (Asbjørnsen 1992). Additionally, natural and human resources required to bring the production system into being are of concern.

According to Asbjørnsen (1992), the interfaces between the product, the production process, and the environment are very important because the interactions across those interfaces are often very strong. A change in product design can have an impact on the production process, and both the product and process have interactions with the physical environment through resource and energy requirements, wastes and emissions, distribution and applications. If a systems engineer whose main stakeholder or “customer” has a major need and requirement for its product to exhibit superior environmental performance, they might seek to consider the material life cycle of the product system in great detail.

A holistic view is necessary in the SE process in order to consider a mix of interrelated life cycles - such as material or cash flow life cycles – in addition to the system life cycle. LCA is an appropriate tool to evaluate environmental dimensions of material life cycles associated with the system. Technical evaluation, including “trade-off” considerations is an important part of SE methodology. LCA methodology and data are important tools to support this technical evaluation (in line with recommendations by Ruth 1998, Bakshi and Fiksel 2003 and Hugo and Pistikopoulos 2005).

Bakshi and Fiksel (2003) discuss how Process Systems Engineering (described as a discipline within Chemical Engineering) can evolve and contribute to sustainability, by expanding its multidisciplinary approach to include LCA as part of evaluating the broader impact of engineering decisions and industrial activity. They stress the importance for sustainability of a new generation of engineers that are trained to adopt a holistic view of processes as embedded in larger systems. Hugo and Pistikopoulos (2005) propose a mathematical programming-based methodology for including LCA criteria within strategic investment decisions for the design and planning of supply chain networks. LCA is used to formulate and evaluate appropriate environmental performance indicators, and an example illustrates how the set of compromise solutions can form an environmentally conscious basis for investment decisions associated with strategic supply chain planning and design. Fet et al. (2010) describe how systems engineering methods, with input from LCA, can create a framework for environmental analysis and comparison for different food products.

2.2 Regulatory Toxicology

The regulatory toxicology theory in this chapter is based on Van Leeuwen and Vermiere (2007). This information is presented in order to familiarise the reader with theory and methods that are background for REACH. This will also clarify the connections to life cycle impact assessment (Chapter 2.3). Regulatory toxicology is concerned with risk assessment and risk management. The risk management process consists of the steps illustrated in Figure 2.2.

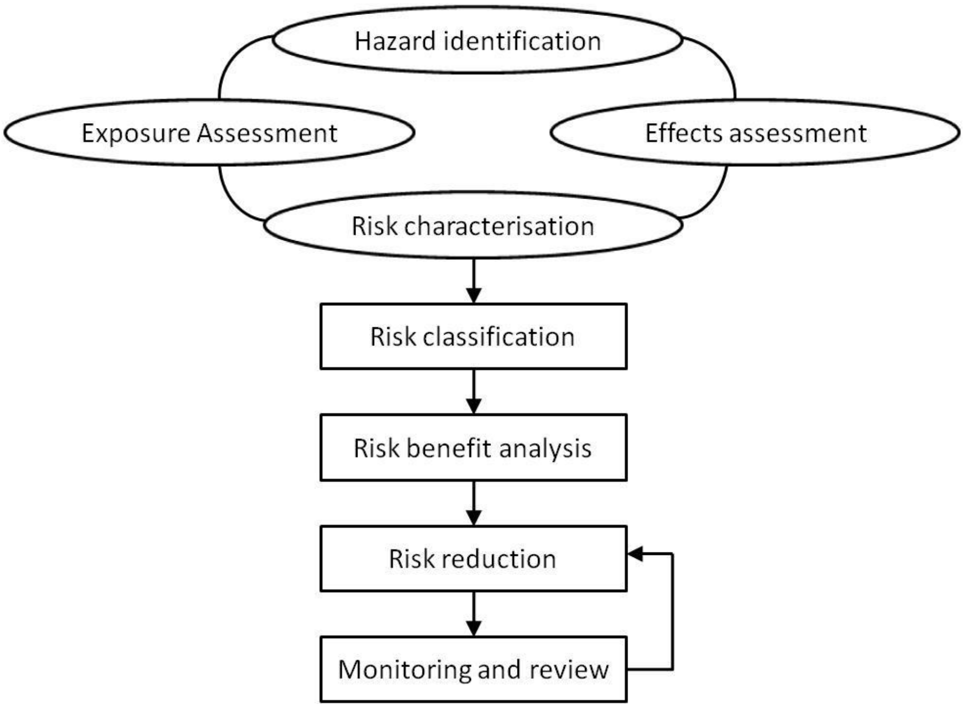

Figure 2.2 Steps in the risk management process (from Van Leeuwen and Vermiere 2007).

Hazard identification is concerned with the inherent capacity for substances to cause adverse effects. Identification of the adverse effects involves gathering data on the types of health effects caused by a substance and the exposure conditions under which environmental damage, injury or disease will occur. A hazardous substance does not present a hazard without exposure. Exposure assessment concerns measuring exposure concentrations once substances are produced, used and emitted. Predictions can also be used - estimating emissions pathways, rates of movement of a substance and its transformation or degradation. Characteristics of the human populations or environmental compartments that are exposed, also the magnitude and duration of the exposure, are important. Effects assessment is also called dose-response assessment, which is the estimation of the relationship between the level of exposure (dose) and the extent of a toxic effect or disease. No effect levels (NELs) can be derived from studies in laboratories, which are converted into predicted, or estimated NELs (PNELs, or DNEL[4]s) for humans or the environment by applying assessment factors. Environmental risk assessment (ERA) requires the estimation of these levels for many species. The complexity of ERA is often simplified by deriving PNECs (predicted no effect concentrations) for the environmental compartments: water, sediment, soil and air.

Risk characterisation examines the significance of actual or predicted exposure to a substance, by using PEC[5]/PNEC risk quotients to estimate the incidence and severity of adverse effects likely to occur in a human population or environmental compartment. This means that risks are only assessed “in a very general and simplified manner. In fact the best we can do is provide a *relative risk ranking*” (Van Leeuwen and Vermiere (2007). Characterisation of risk is thus similar to characterisation in LCA, where emitted substances are relatively ranked according to the effects they can have compared to a reference substance (for example CO_2 for global warming potential).

[4] Derived no effect level
[5] Predicted Environmental Concentration

Risk classification is described as the valuation of risk, to decide if risk reduction is required. The acceptability of risk is a value-laden issue. Two risk levels are commonly associated with this exercise; the upper limit (maximum permissible level, MPL) and the lower limit (the negligible level, NL). If these levels are used it is common to accept risk below the NL, but require the use of risk management measures (RMM) above this level. Levels above the MPL are defined as unacceptable.

If risk reduction options are required risk-benefit analysis is used. The options for risk reduction can range from slight adaptation of the production process, or intended use of the substance to a complete ban on production or use of a substance. Technical feasibility, social and economic factors, ethical and cultural values, legislative/political factors and scientific aspects must be considered in risk-benefit analysis. Cost-benefit analysis is also widely used within the approach, estimating the net benefits (or costs) to society of a proposed restriction compared to the baseline. Risk reduction encompasses many different approaches, including: classification and labelling, safety or quality standards, risk management measures (RMM, i.e. redesign of processes, closed systems, workplace restrictions, instructions and information about safe use, gas masks, filter masks, goggles, gloves or limiting the concentration of a substance in a preparation or article).

Monitoring and review is the final step in the risk management process illustrated in Figure 2.2- Monitoring is described as repetitive observation of one or more chemical or biological elements over space and time according to a pre-arranged schedule. Other ways of reviewing environmental and health management measures include audits and inspections, product registers, performance measurements and indicators for human health and sustainable development.

Environmentally-sound management of toxic chemicals as recommended by UNCED (United Nations 1992 in Van Leeuwen and Vermiere 2007) consists of the following points:

a) Expanding and accelerating the international assessment of chemical risks
b) Harmonization of classification and labelling of chemicals
c) Information exchange on toxic chemicals and risks
d) Establishment of risk reduction programmes
e) Strengthening of national capabilities and capacities for management of chemicals
f) Prevention of illegal traffic in toxic and dangerous products

The REACH regulation is the European Union (EU) answer to some of these challenges. Recommendations a) - c) are incorporated in the REACH and the Classification, Labelling and Packaging regulations (CLP regulation, Commission of the European Communities 2008).

2.3 Life Cycle Assessment and regulatory toxicology

ISO 14044 (2006) describes Life Cycle Assessment (LCA) as a technique for better understanding and addressing the environmental impacts associated with products and services. It is a standardised method with a clear focus on the function of a product or service, with the intention of minimising total environmental impacts associated with fulfilling this function.

Life Cycle Assessment is carried out in phases; goal and scope definition, inventory analysis, impact assessment and interpretation (ISO 14044 2006, European Commission 2010a, Baumann and Tillman 2004). Figure 2.3 illustrates the framework for LCA.

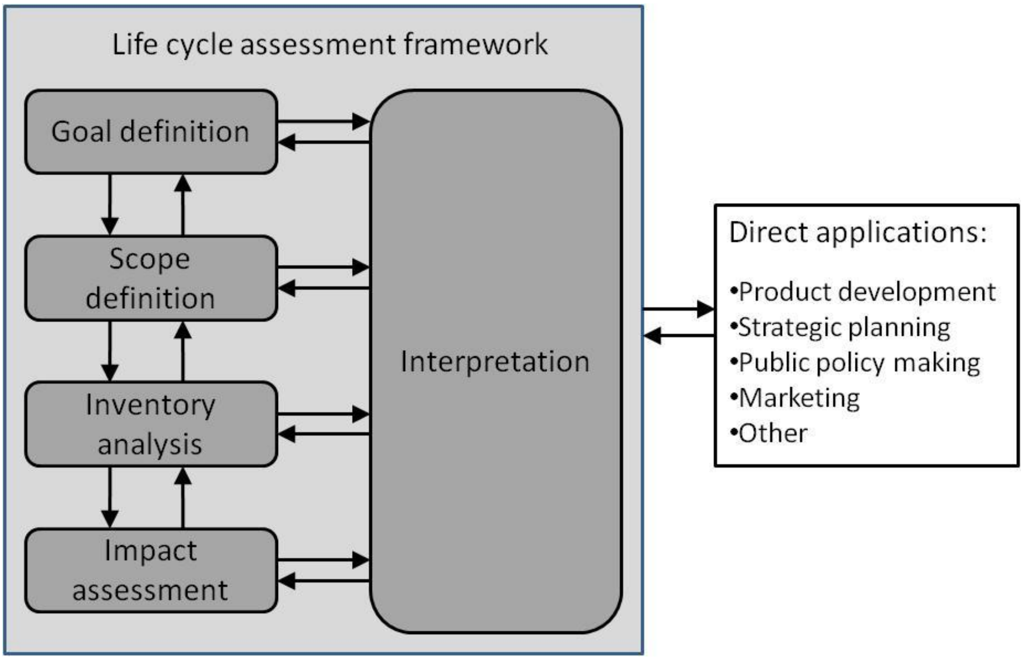

Figure 2.3: Framework for LCA (European Commission 2010a, modified from ISO14040 2006).

This framework is described in depth in various references (for example Baumann and Tillman 2004, European Commission 2010a), so only a brief description will be given here. Goal and scope definition provide information about the product to be studied, the purpose of the study, its intended application, the reason it has been carried out and to whom the results are intended to be communicated. It is important that the goal and scope are clearly defined and consistent with the intended application.

Inventory analysis is where information about the environmental accounts of the system is gathered. It is an incomplete mass and energy balance for the system (Baumann and Tillman 2004) – incomplete in that only the environmentally relevant flows are considered. Data for relevant inputs and outputs of raw materials, energy carriers, products, waste and emissions are collected and related to the functional unit for the product system. The functional unit is defined as the "quantified performance of a product system for use as a reference unit" (ISO 14044 2006). The functional unit is part of the scope of the study and provides a reference to which the input and output data are normalised.

Impact assessment consists of classification, characterisation and weighting (the latter being optional). Classification is where the inventory parameters are sorted according to the type of environmental impact they contribute to ("which impacts are relevant"). Characterisation is where the relative contributions of the emissions and resource consumptions are calculated ("how much do the flows contribute"). Weighting can be used to interpret or further aggregate the results from characterisation. Baumann and Tillman describe weighting as a "yardstick" with which environmental problems are measured. Such "yardsticks" are based on expressed values and preferences concerning environmental issues.

LCA studies can be performed using either an attributional or a consequential approach (European Commission 2010a). The choice of the approach should be guided by the purpose of the study and has consequences for how the LCA is executed (for example what type of data to include).

Wenzel (1998) argued that the actual consequences of a decision derive from the changes in inputs and outputs from the industrial system, thus requiring marginal data for the various processes modelled. However, according to Ekvall et al. (2005) the retrospective (or attributional) approach is appropriate when the decision concerns avoiding environmentally poor systems (systems with an undesirable environmental impact). They also argue that activities that the decision-maker can only marginally affect should be modelled using marginal data (the consequential approach); whereas activities for which decision-makers can make complete changes should be modelled using average data. It is also maintained that the attributional approach is most appropriate for accounting for product improvements; whereas the consequential approach can be detrimental to producers that initiate, or maintain good production systems, as it may not allow for these producers to benefit from this “good” behaviour.

As described briefly above, life cycle impact assessment consists of classification, characterisation and weighting. This section is concerned with the links between regulatory toxicology and human health and ecosystem impact assessment parts of LCIA. Other impacts and the weighting of environmental impacts in relation to each other are not considered here.

LCIA results are calculated by multiplying the individual inventory data (life cycle inventory results) by characterisation factors (European Commission 2010a). A characterisation factor linearly expresses the contribution to an impact category of a quantity of a chemical released into the environment (Pennington et al. 2006). This factor is chemical specific and can also be a function of when and where an emission occurs. There are several models available for characterisation factors, both for human health and ecosystem impact potentials. The European Commission Joint Research Centre has published an overview of the currently relevant LCIA models (European Commission 2010b). This is a background document for the as-yet incomplete work on recommendation of methods for LCIA in a European context (European Commission 2011).

LCIA characterisation factors are based the following equation (Pennington et al. 2006):

$$\underset{\substack{\text{Characterisation}\\ \text{Factor}}}{\underset{\uparrow}{\frac{Impact}{Emission}}} = \underset{\substack{\text{Fate}\\ \text{Factor}}}{\underset{\uparrow}{\frac{Mass\ Distribution}{Emission}}} \times \underset{\substack{\text{Exposure}\\ \text{Factor}}}{\underset{\uparrow}{\frac{Intake}{Mass\ Distribution}}} \times \underset{\substack{\text{Exposure} - \text{response}\\ \text{Factor}}}{\underset{\uparrow}{\frac{Incidence}{Intake}}} \times \underset{\substack{\text{Consequence}\\ \text{Factor}}}{\underset{\uparrow}{\frac{Consequence}{Incidence}}} \tag{1}$$

Characterisation factors based on methodologies that were developed to support regulatory assessments can be expressed by (Pennington et al. 2006):

$$Characterisation\ factor = \frac{\left[{}^{PEC}/_{PNEC}\right]_x}{\left[{}^{PEC}/_{PNEC}\right]_{\mathrm{ref}}} \tag{2}$$

where *x* is the chemical for which the characterisation factor is derived and *ref* is the reference substance. This approach means that inventory data are weighted in terms of regulatory-based hazards. Pennington et al. (2006) give an example of the use of this type of characterisation factor, where a characterisation factor of 10 would mean a chemical had a regulatory hazard ratio (PEC/PNEC risk quotient) of 10 times that of the reference chemical. However this would not necessarily mean that the risk or potential consequences of a toxicological effect would be 10 times higher. This ratio does not provide a measure of relative risk of one substance to another, but rather how much further away one substance was from its limit value than the other substance is from its own (different) limit value. LCA aims to provide insights for products that are complementary to regulatory-, site- or process oriented risk assessments; whether or not current regulatory limits will be exceeded at specific locations or points in time is not the focus of an LCA.

The USEtox™ model has been used for the case study presented in Askham (2011b). In contrast to the above, this model uses risk-based characterisation factors. USEtox is a consensus model for chemical impact characterisation related to human toxicity and freshwater ecotoxicity (Rosenbaum et al. 2008, USEtox 2011). It is a result of the United Nations Environment Programme (UNEP)-Society for Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative. Pizzol et al. (2010) provides an overview of different existing LCIA methodologies. This shows how USEtox builds upon EcoIndicator 1999 (Goedkoop and Spriensma 2000), Impact 2002+ (Jolliet et al. 2003), EDIP 97 (Wenzel et al. 1997, Hauschild and Wenzel 1998) and TRACI (Bare et al. 2003). As described in Pizzol et al. (2010), USEtox is not a complete, standalone, LCIA method, as it includes only human toxicity and ecotoxicity, but it is a multimedia model that can assess both fate and exposure for a number of chemical emissions. Figure 2.4 shows the USEtox framework for comparative toxicity assessment (Rosenbaum et al. 2008).

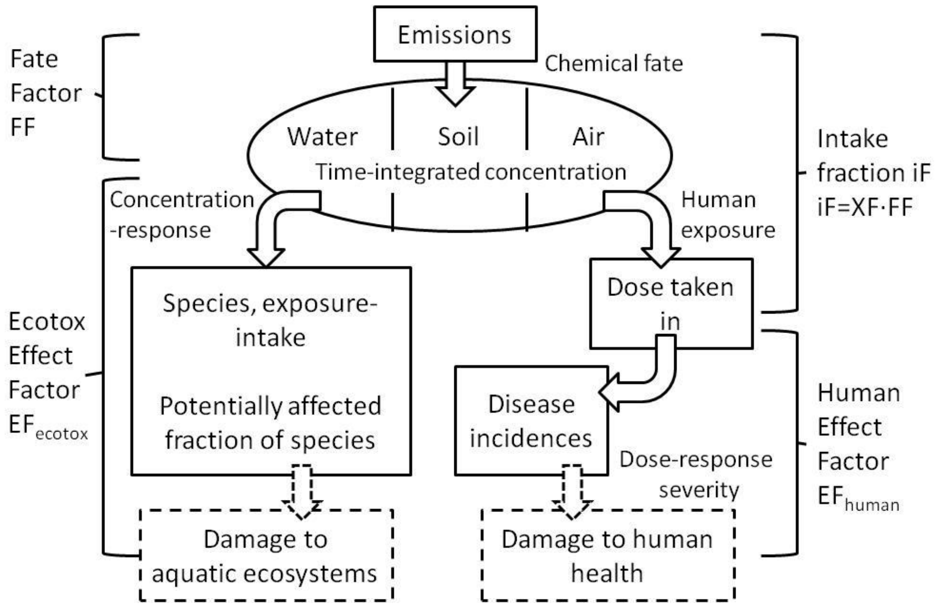

Figure 2.4 USEtox framework for comparative toxicity assessment (Rosenbaum et al. 2008).

In USEtox the cause-effect chain is modelled using matrices of fate ($\overline{FF}$ in day), exposure ($\overline{XF}$ in day^{-1}, human toxicity only) and effects ($\overline{EF}$ in cases/kg$_{intake}$ for human toxicity, or PAF[6] m^3/kg for ecotoxicity). This results in a set of scale-specific characterisation factors ($\overline{CF}$ in cases/kg$_{emitted}$) as shown in Equation 3 (Rosenbaum et al. 2008):

$$\overline{CF} = \overline{EF} \times \overline{XF} \times \overline{FF} = \overline{EF} \times \overline{\iota F} \qquad (3)$$

USEtox has been described as a new generation toxicity model for LCA, springing out of Leiden University's CML 2000 and Pré Consultants Eco-Indicator (Huijbregts et al. 2005, Van de Meent

[6] potentially affected fractions of species

and Huijbreghts 2005, USEtox 2011). The factors used in the USEtox LCIA method for human toxicity and ecotoxicity are based on three elements:

1. Fate factors, calculated using USES-LCA 2.0[7]
2. Ecotoxicity effect factors, based on HC_{50}[8]
3. Human toxicity effect factors, based on ED_{50}[9] and extrapolation from NOEL[10] and LEOL[11]

2.4 Comparing REACH and Risk Assessment with LCA

The previous sections have given short descriptions of REACH, regulatory toxicology (risk assessment of hazardous chemicals) and LCA. This section outlines some of the important differences between REACH / risk assessment and LCA.

The REACH regulation applies to chemicals on a tonnage basis, whereas LCA has a functional and life cycle focus. In REACH, the "function" of a chemical is interpreted as a description of its use. In contrast, the "function" in LCA is the purpose that the product is designed to fulfil; it is then possible to calculate the amounts of materials and chemicals required (reference flows in LCA terminology). The potential hazards associated with chemicals and the amounts produced, or imported, determine the level of documentation and testing required for the REACH approval of their use by ECHA.

In LCA, the functional unit is defined as the "quantified performance of a product system for use as a reference unit" (ISO 14044 2006). The functional unit is part of the scope of the study and provides a reference to which the input and output data are normalised. LCA approaches the environmental impacts of products and services with a clear focus on the function for the user (ISO 14044 2006, Baumann and Tillman 2004). REACH is concerned with quantities of chemicals and their properties, independent of the amount needed to fulfil a function over a period of time. The functional approach is essential when considering substitution of a given chemical, or substance. It is possible that a substitute chemical has lower toxic impacts per kilogram, but more of it is required in order to fulfil the same function. In such cases, substituting one substance with another that seems to be less hazardous can lead to a total increase in environmental impacts throughout the life cycle, when the functional perspective is included. As long as the substitute substance is already approved for the particular use, the demand for exposure scenarios[12] in order to fulfil REACH requirements would not be affected. If the chemical is significantly less hazardous the demand for exposure scenarios could in fact be reduced. It is therefore vital that the life cycle approach is considered together with the implications of REACH in order to ensure real improvements in the functional and holistic environmental profiles of products used in society. Thus it would seem that the response to REACH could greatly benefit from the functional approach used

[7] A 'nested multi-media fate, exposure and effects model' described in Van Zelm et al. (2009).
[8] The median hazardous concentration affecting 50% of the species.
[9] The chronic dose of a substance with mode of action affecting 50% of the human population.
[10] NOEL = No observed effect level
[11] Lowest observed effect level
[12] Exposure scenario definition: "the set of conditions, including operational conditions and risk management measures, that describe how the substance is manufactured or used during its life-cycle and how the manufacturer or importer controls, or recommends downstream users to control, exposures of humans and the environment. These exposure scenarios may cover one specific process or use or several processes or uses as appropriate" (Commission of the European Communities 2007).

in LCA. It appears that if REACH was implemented in companies without exploiting the functional and life cycle approach and potential synergies from LCA, this could lead to suboptimal solutions (both in terms of implementation of the REACH directive in companies and product development). LCA methodology is also often used in order for companies to focus on improvements for product systems. This is another aspect of LCA methodology that could provide positive influence on REACH implementation, by contributing to the inclusion of an innovative improvement perspective.

REACH Chemical Safety Reports (CSR) document Hazard Assessment and Exposure Assessment (see Figure 1.1). Under REACH, registrants of substances are obliged to collect and submit all relevant and available information on the intrinsic properties of a substance, including: physico-chemical properties, exposure/uses/occurrence and applications, mammalian toxicity, toxicokinetics, ecotoxicity, and environmental fate, including chemical and biotic degradation (ECHA 2008b). The data requirements for USEtox are such that it should be possible to obtain much useful data from REACH CSRs. However, it is highly possible that many of the details needed for REACH (such as exposure scenarios) will be confidential, while the results (e.g. use of gloves, wearing of safety glasses) will be public. The fate and exposure models being developed in connection with REACH should also yield some data that will provide useful input in LCA fate, exposure and effect models (e.g. USES-LCA). It has been demonstrated that differences between the potential consequences of toxicological effects could be taken into account in LCA using common measures such as Disability Adjusted Life Years per incidence (DALY, Hofstetter in Pennington et al. 2006). The LCA approach results in factors for DALY, whereas REACH information results in advice on protective equipment. The advice given in SDS/eSDS[13] as a result of REACH should reduce the exposure to a level that results in no actual effects (i.e. any exposures at levels below those that give an effect). These two approaches (LCA and REACH) are currently based on similar information, but with very different aims.

The differences and commonalities in LCA and risk assessment (RA) have been examined by several authors (for example Wegener Sleeswijk et al. 2001, Olsen et al. 2001, Hofstetter et al 2002, Cowell et al 2002, Hertwich et al. 2001). It is important to note that the impact assessment part of LCA is analysing the potential environmental impacts that are caused by interventions that cross the border between technosphere and ecosphere and act on the natural environment and humans. Any potential environmental impacts are caused after fate and exposure steps. The results of LCIA should be seen as environmentally relevant impact potential indicators, rather than predictions of actual environmental effects (ILCD Handbook, European Commission 2010a). LCA and LCIA are described in the ILCD Handbook as distinct from risk based, substance specific instruments. Bare (2006) describes the commonalities between LCIA and human health risk assessment as the basis for the modelling. LCIA can be described as more comprehensive than human health risk assessment, as it covers a larger number of impacts, stressors and locations. The more comprehensive coverage of LCIA results in a decreased level of certainty.

The role of human health RA is to protect the local population by not exceeding a certain acceptable level of risk (as described in the risk classification step of risk management in Chapter 2.2), whereas the role of LCIA is to provide relative comparisons, and identify from where the primary sources of potential impact are projected (Olsen et al. 2001, Bare 2006, Pennington et al. 2006). Human health RA can be overly protective of local populations using assumptions that err on the side of higher dosages calculated, whereas LCIA may try to represent more of the average

[13] Safety data sheets/extended safety data sheets, see Figure 4.4

impact on society (Bare 2006). RA also often takes background concentrations into account and can thus give absolute risk calculations. LCIA's broader perspective means that background concentrations are generally not incorporated, but LCIA can provide a view of the emissions occurring over the full life cycle. Site specific air dispersion models and groundwater models in RA are typically more sophisticated and can strengthen the accuracy of LCIA models (Owens 1997). LCA cannot address threshold issues, or actual quantification of risk, but it is described as doing a better job of calculating the potential for marginal risks for a large number of stressors and emission locations (Bare 2006).

2.5 Product Development and Ecodesign

The theoretical approaches and methodologies presented in this thesis are required in order to address environmental product development combining the life cycle approach with chemical hazard information. It is therefore natural to include product development and Ecodesign in this chapter. UNEP's Ecodesign manual (Brezet et al. 1997) is a central reference for the information presented here. The term Ecodesign is used for "cases where the environment becomes a co-pilot in product development and design decisions". The steps involved in an Ecodesign project are shown in Figure 2.5. The Ecodesign manual has limited the number of standard terms and basic principles with which the environment is linked to the design process. The three standard sets of basic principles included are: sustainable development, the life cycle approach, and cleaner production. The latter is described as the continuous application of a preventative environmental strategy to production processes and products to reduce risks to people and to the environment.

Drivers for Ecodesign, such as legislation, increasing demands from customers and the possibility of cost savings are all direct links between Ecodesign and general corporate strategy. Brezet et al. (1997) describes the synergies between Ecodesign, cleaner production, EMS[14] and quality management, as well as the clear common ground between Ecodesign and occupational health and safety and logistics. The work presented in this thesis addresses several of these aspects. Tools for linking legislation and occupational health and safety (i.e. REACH and CLP risk labelling) with Ecodesign will be presented and exemplified in Chapter 3.

The links between the systems engineering approach and the Ecodesign process shown in Figure 2.5 are clear when comparing this with the "System Life Cycle" and the "Innovation Life Cycle" in Figure 2.1. Conceptual design, search for solutions, performance measures and detailed design are all steps in the System life cycle in Figure 2.1. These are closely linked to selection of the product, defining the design brief (Step 2, Figure 2.5). Performance measures would have application in Steps 3-7. Step 5 would clearly involve detailed design. The innovation life cycle in Figure 2.1 includes idea generation, idea screening, concept development, premarket testing and financial analysis, as well as product development. These steps in the innovation life cycle link to steps 3-6 in the Ecodesign process below.

[14] Environmental Management Systems

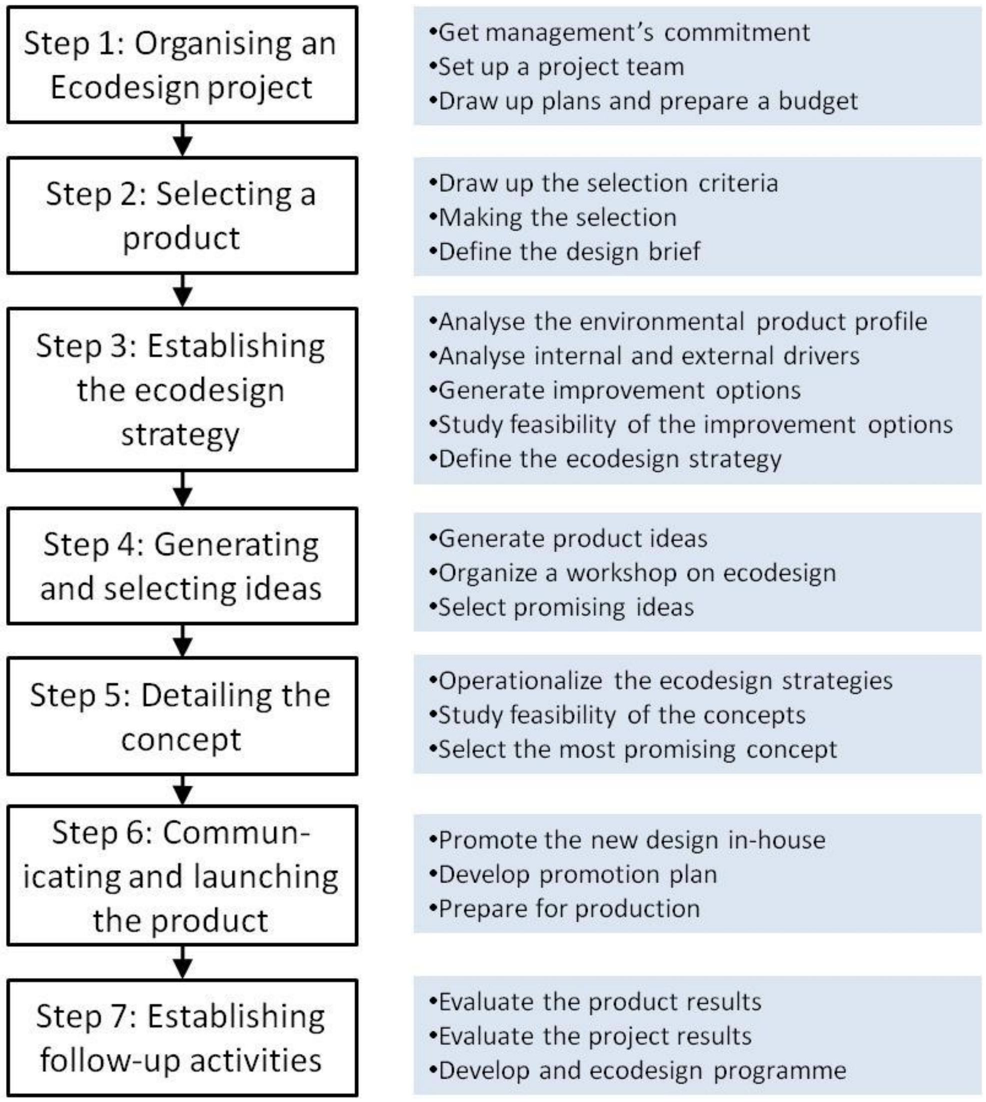

Figure 2.5: The steps involved in an Ecodesign project (Brezet et al. 1997).

The work presented in this thesis has provided tools that can provide important information to support steps 2-4 in Figure 2.5. The Strategy Tool presented in Askham et al. (2011a) supports Step 2 (selecting a product) and is based on the Eco-portfolio matrix (Brezet et al. 1997). The Boston Consulting Group's general Growth-Share Matrix (Kotler in Brezet et al. 1997) inspired the Eco-portfolio matrix presented by Brezet et al. (1997) and the portfolio strategy matrix (Hedley in De Wit and Meyer, 2004). The links between Ecodesign, REACH, LCA and systems engineering are exemplified in Chapter 3.

Hanssen (1997) focuses on integrated product development and systems design and describes how environmental aspects can be integrated in product development (for example Figure 2.1) from idea generation to the finished product. It is vital to combine quality function approaches with life cycle environmental information, and ensure that this is included at important decision-making stages in the product development process. The systems engineering approach has strong links to the life cycle approach and the Ecodesign approach shown above. Behrendt et al. (1997) also supports the importance of integration, stating that Life Cycle Design (LCD) must be integrated into the design culture of a company, and that organisational aspects are critical to its success.

Giudice et al. (2006) provide a good overview of the types of tools and approaches available for a life cycle approach to product design. However, toxicity and chemical hazard is not specifically adressed. They also describe additional issues of strategic importance. Human health and environmental hazards are examples of what can be included in multicriteria approaches, where design solutions are developed to combine a variety of diverse criteria (conventional performance, quality and cost, as well as environmental). Giudice et al. (2006) also describe trade-off levels, where design choices have the aim of achieving efficient compromise between different product requirements, which can be environmental, technical, quality-related, economic and social. This is also a typical situation with links to the trade-off considerations described in Chapter 1.3, which require the product designer to consider multiple criteria in this technical evaluation (also connected to the feasibility of improvement options in steps 3 and 4 of the Ecodesign process, Figure 2.5).

3 Jenson A/S: An Illustrative Case Study

In order to give a comprehensive example of how the work presented in the papers fits together and answers the research questions in Chapter 1.1, a fictitious company is used. Jenson A/S has a range of products that are sold to professional buyers in the construction industry. This case study has required inventing a set of fictitious products, with specified chemical compositions and other data required for this exercise. In this case study Jenson A/S has noticed that their competitors have started to win contracts largely on the basis of providing sound environmental impact information. They also feel pressure to be providing information about the chemicals in their products and have had a lot of enquiries from customers and suppliers in relation to the REACH regulation. One approach that Jenson A/S has used has been to access building industry and chemical industry guidelines and factsheets, composing a standard letter that can be sent out to answer enquiries on these issues. This has proven practical in enabling a swift response to enquiries from actors up and down their value chain, but the product development team at Jenson A/S are very much aware of the need to take a more pro-active approach. This chapter charts their progress, using tools presented in Askham et al. (2011a, 2011b and 2011c).

3.1 Strategy

The management team at Jenson A/S sought an overview of how their products performed according to specific indicators. The Strategy Tool from Askham et al. (2011a) was chosen as the basis for providing an overview of the product portfolio. The tool is a strategy matrix tool in a similar form to the Eco-portfolio matrix presented by Brezet et al. (1997). The matrix includes an indicator for environmental quality and an indicator incorporating three different REACH aspects. Jenson A/S decided to use global warming potential as the environmental quality indicator for this exercise, as market research showed that many of their customers were primarily interested in carbon footprint. The management team at Jenson A/S was presented with the Strategy Tool results as shown in Figure 3.1, with explanation of the included indicators given after the figure.
The annual turnover of the different products is represented by the size of the spheres in the Strategy Tool diagram. Thus management can also see at a glance the relative importance of products in their portfolio, alongside the other indicators. Figure 3.1 shows that the products with the highest turnover are Jenson Special A, Jenson Additive 1, Jenson Economy and Jenson Economy Plus.

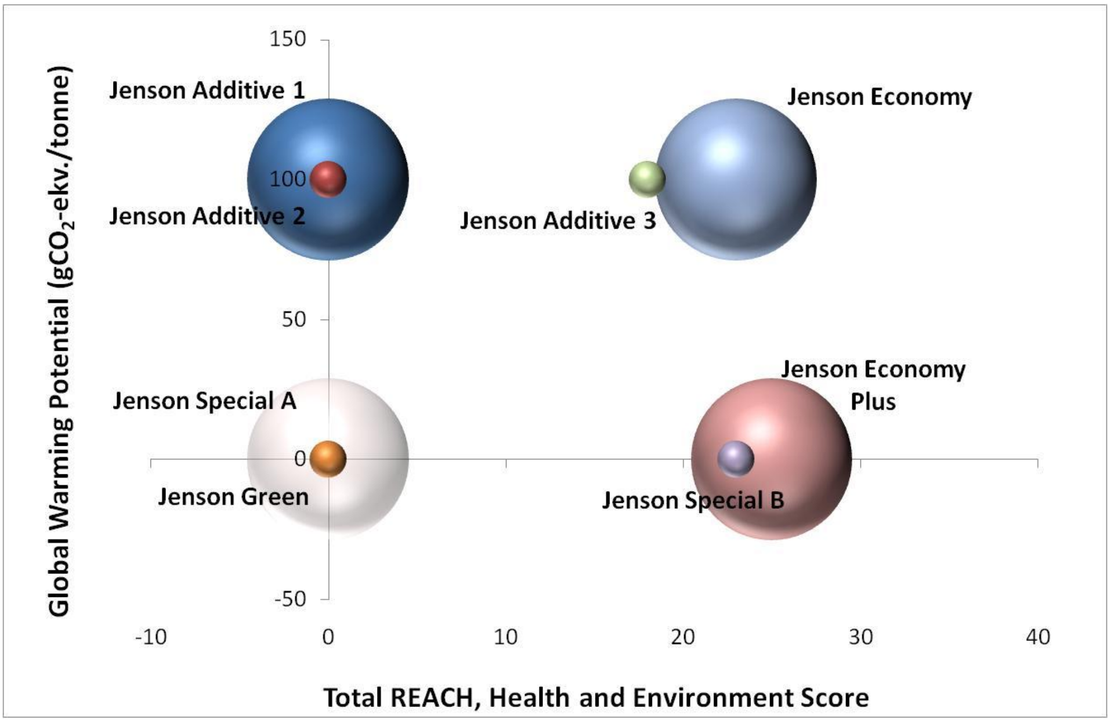

Figure 3.1: Strategy Tool results for Jenson A/S products (based on Askham et al. 2011a and Askham et al. 2011c).

The results show that Jenson Green performs extremely well in terms of global warming potential (GWP) and chemical hazard (Total REACH, health and Environmental Score). Assuming market scope for this product exists, marketing efforts focussing on its excellent GWP and chemical hazard performance might prove especially fruitful. Both of the Jenson Economy products perform poorly for chemical hazard, although Jenson Economy Plus performs well for GWP. These are high volume products in high volume markets with considerable competition. Environmental and chemical hazard performance could be important competitive factors in defending or increasing market share. This makes these high volume products interesting for product development. The chemical hazard aspects of this product development will be examined more closely in Chapter 3.2. Jenson Additive 1 is a high volume product that has a good chemical hazard performance, but a relatively poor performance for GWP. This product's life cycle GWP data should be examined closely to see what improvements can be made. Jenson Additive 2, Jenson Additive 3 and Jenson Special B have low sales volumes. Assuming there is scope for increased sales of these products, the Strategy Tool identifies relative strengths in environmental and chemical hazard performance (to be highlighted in marketing efforts) and weaknesses (to be considered in product development). The Strategy Tool also identifies Additive 3 as a product that performs poorly in all three dimensions shown (GWP, chemical hazard and sales volume). This might be a candidate product for phase-out. A process to support existing customers will be important, preferably encouraging them to choose another, better-performing product.

The Strategy Tool aids Jenson in rapid evaluation of economic and environmental features of its product portfolio. The data acquired in this exercise can help support Jenson A/S staff dealing with customers during the process of phase-out and product change. Valuable information is assembled for each axis, and the company gains additional knowledge about relevant dimensions concerning their products' environmental performance.

The indicators used to construct the Strategy Tool overview are given in Table 3.1, along with the rubric for deriving scores from relevant data. The scale for REACH Complexity, which depends on the number of exposure scenarios required, is also shown. Exposure scenarios are required if company products contain chemicals that meet certain criteria: they require chemical safety reports under REACH and meet the criteria for classification as dangerous, or are assessed to be a PBT (persistent, bioaccumulative and toxic) or vPvB (very persistent and very bioaccumulative), and are contained in the products above specified limits (Article 14, Commission of the European Communities 2007).

For Health Hazard Class and Environmental Class the R-phrases are grouped into the categories low, medium and high (Askham et al. 2011a). Weighting of the categories is the result of an expert assessment by Jenson A/S. The experts judged very toxic, toxic by prolonged exposure, sensitization and CMR effects as so severe so as to carry a rating of 10; toxic, harmful and irritating effects carry weight 3, and harmful, irritating effects carry weight 1. This weighting is in line with Askham et al. (2011a) and similar to Saling et al. (2002), where the R-phrases were grouped according to hazard levels, but a logarithmic scale was applied.

Table 3.1: Strategy Tool matrix indicators (based on Askham et al. 2011a and Askham et al. 2011c).

Axis	Comment	Indicator	Definition
x-axis: Total REACH, Health and Environmental Score	The sum of the indicators REACH Complexity, Health Hazard Class and Environmental Hazard Class.	REACH Complexity	The number of exposure scenarios required for the product (Article 14, Commission of the European Communities 2007), scores assigned: 0 exposure scenarios = 0; 1-2 exposure scenarios = 1; 3-5 exposure scenarios = 5; more than 5 exposure scenarios =10.
		Health Hazard Class	Based upon the risk phrases (R-phrases) for effects on human health and the environment associated with chemicals in line with European hazard labelling directives (Council Directive 67/548/EEC, Directive 1999/45/EC). The R-phrases are grouped into three risk categories: low, medium and high. Table E.3-1 REACH CSA guidance (ECHA 2008a) and COSHH (HSE1999). The R-phrases hazard level classifications are weighted: low, medium and high hazard levels are assigned the values 1, 3 and 10 respectively (based on expert judgement at Jenson A/S).
		Environmental Class	
y-axis: Environmental Merit		CO_2-equivalents	Life cycle assessment-based data for the global warming potential for Jenson A/S' products.

Table 3.2 shows the basis for some of the Jenson A/S input data for the Strategy Tool. The number of exposure scenarios required for a given product is dependent on the specific use of the product and the different types of exposure patterns. Exposure scenarios are "a set of information describing the conditions under which the risks associated with the identified use(s) of a substance can be controlled. It includes operational conditions (for examples the duration and frequency of use or the amount used, the process temperature or the pH) and necessary risk management measures (e.g. local exhaust ventilation or a certain type of glove, waste water and gas

treatment).” (ECHA 2008c). If a product contains no substances that have a risk classification, then no exposure scenarios are needed (as for Jenson Additive 1 and 2). The relevant R-phrases for each of the products are also given in Table 3.2. These R-phrases are found on the safety data sheets (SDSs) for the raw materials, in combination with the software package that Jenson A/S already uses to compile their own SDSs for their products.

Table 3.2: Exposure Scenario and R-phrase Data for Jenson A/S products.

Product	**No. of exposure scenarios required**	**R-phrases that apply to the product**	**Health and environmental hazard classifications** (Askham et al. 2011a)
Jenson Additive 1	0	-	
Jenson Additive 2	0	-	
Jenson Additive 3	3	R21, R34, R36, R38, R41, R43, R52/53, R53	Health hazard classification: R21, R36, R38 low; R34, R41, R43 medium. Environmental hazard classification: R52/53 medium, R53 high.
Jenson Special A	0	-	
Jenson Special B	7	R20, R21, R22, R36, R38, R41, R43, R48/22, R50, R50/53, R51/53, R68	Health hazard classification: R21, R21, R22, R36, R38 low; R41, R43, R48/22 medium; R68 high. Environmental hazard classification: R50, R50/53 low; R51/53 medium.
Jenson Green	0	-	
Jenson Economy	6	R21, R22, R34, R36, R38, R41, R43, R52/53, R53	Health hazard classification: R21, R22, R36, R38 low; R34, R41, R43 medium. Environmental hazard classification: R52/53 medium, R53 high.
Jenson Economy Plus	4	R53, R68	Health hazard classification: R68 high. Environmental hazard classification: R53 high.

The scoring system shown in Table 3.1 is applied to the information given in Table 3.2 providing the REACH Complexity, health and environmental risk indicator scores shown in Table 3.3. This table also includes the LCA-based global warming potential data Jenson A/S has calculated for their products, as well as the annual turnover for these products.

The total REACH, health and environment score (x-axis in Figure 3.1) for Jenson A/S’ products is calculated by the following equation:

$$\begin{matrix} Total\ REACH, Health \\ and\ Environment\ Score \end{matrix} = \begin{matrix} REACH \\ Complexity \end{matrix} + \begin{matrix} Health\ Hazard \\ Class \end{matrix} + \begin{matrix} Environmental \\ Class \end{matrix} \qquad (4)$$

The choice and combination of these indicators is described and discussed in Askham et al (2011a). The methods, motivation and weightings implied in the scoring system in Table 3.1 and Equation 4 are also addressed in this reference. Equation 4 indicates that the REACH Complexity, health and environmental indicators used are given equal weight. Different companies performing this type of strategic analysis may have other priorities and choose to weight these REACH aspects differently. The company has decided to adopt this equal weighting, as used by Jotun, for their first trial of this tool. This weighting will be considered in a review of the process in order to give feedback to future Ecodesign processes at Jenson A/S.

Table 3.3: Data required for the Strategy Tool.

Product	REACH Complexity	Health Hazard Class	Environmental Class	CO_2-equivalents (kg/tonne)	Annual Turnover in 1000 NOK
Jenson Additive 1	0	0	0	100	200 000
Jenson Additive 2	0	0	0	100	10 000
Jenson Additive 3	5	3	10	100	10 000
Jenson Special A	0	0	0	≈ 0	200 000
Jenson Special B	10	10	3	≈ 0	10 000
Jenson Green	0	0	0	≈ 0	10 000
Jenson Economy	10	10	3	100	200 000
Jenson Economy Plus	5	10	10	≈ 0	200 000

The y-axis in Figure 3.1 is global warming potential (CO_2-equivalents column in Table 3.3). As this case study is an illustrative example, values of almost zero (≈ 0) are given in this column. It is of course highly unlikely that any products in a real case would have an LCA global warming potential value of zero.

Considering just one LCA-based environmental indicator may give an incomplete picture. Other priorities may be identified if other environmental merit indicators are used. This issue is discussed and exemplified using LCA-based data for seating products in Askham et al. (2011c).

3.2 Product Development

The strategy work described in Chapter 3.1 identified four products with poor performance for chemical hazard. The Screening Tree Tool presented in Askham et al. (2011b) is suitable for a closer examination of this chemical hazard performance. This Screening Tree Tool combines approaches and tools available in an LCA software tool (SimaPro 7.3, PRé Consultants 2011) with risk phrase information for health and environmental hazards encompassed by REACH and the CLP directive (Commission of the European Communities 2007, Commission of the European Communities 2008). The structure of the method devised for the Screening Tree Tool is illustrated in Figure 3.2. This method structure and the reasoning behind it is described in more detail in Askham et al. (2011b).

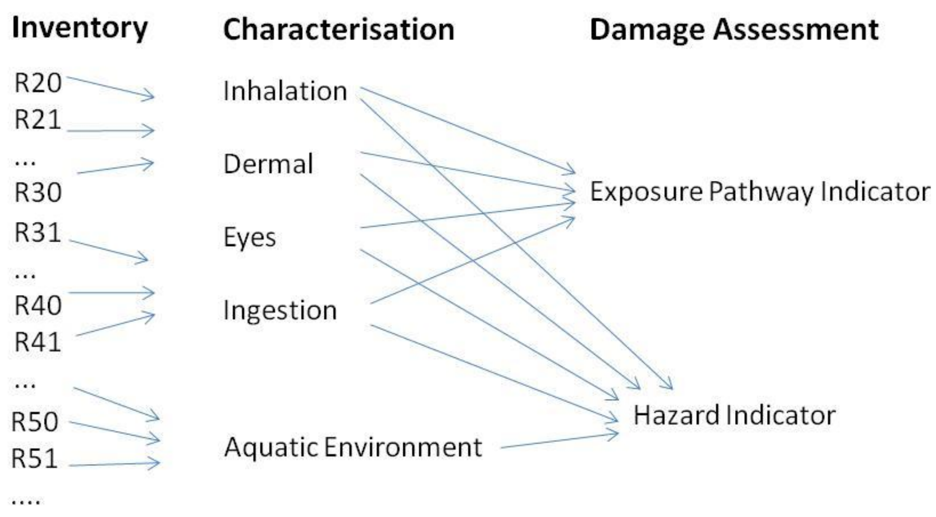

*Figure 3.2: The structure of the method devised for calculation of Hazard Indicator and Exposure Pathway Indicator (*Askham et al. 2011b).

Table 3.2 shows R-phrases that apply to the product. R-phrases apply when they are relevant for a chemical (substance[15]) and this chemical is present in the product (mixture of substances[15]) in quantities exceeding the labelling limit for this substance (Commission of the European Communities 2008). Jenson A/S has identified both the R-phrases that apply to their products, and ones where data were considered, but found to be under the threshold value. The risk phrases considered for Jenson Economy Plus are shown in Table 3.4.

Table 3.4: Risk phrases relevant for Jenson Economy Plus.

Hazard Classification	R-phrases
Health hazard	R20, R21, R22, R36, R38, R34, R41, R43, R48/22, R68
Environmental hazard	R50, R50/53, R51/53, R52/53, R53

Only R68 and R53 actually applied (see Table 3.2), as the limit values for these are relatively low (R68: Possible risk of irreversible effects; R53: May cause long-term adverse effects in the aquatic environment). The information about the product composition and all of the relevant risk phrases (both above and below threshold values) was entered into the Screening Tree Tool. Figure 3.3 shows the Hazard Assessment results for Jenson Economy Plus.

The thickness of the red arrows in Figure 3.3 represents the Applicability Ratio (quantity present/limit for classification) for the given chemical in the product (Askham et al. 2011b). The numbers in the bottom left of the product tree boxes in Figure 3.3 give the Applicability Ratio data. The bottom level shows the sum for a given R-phrase (for example R38 has a total applicability ratio of 0.425, this is a result of R38 applying both to chemicals 1 and 3). The figure shows that the relevant labelling for Jenson Economy Plus stems from the presence of chemicals C1 and C3, and ultimately from risk phrases R53 and R68 (which have applicability ratios greater than 1.0). The other R-phrases would not apply to the product, but this overview of their relative importance is important for product development. If C3 could be replaced with a functionally-equivalent but less hazardous alternative, Jenson Economy Plus would both improve its Total Reach, Health and

[15]REACH definition

Environment Score and present a less severe occupational health hazard to construction industry workers. The Screening Tree tool indicates that any candidate replacement chemical should be considered particularly in light of risk phrase R68. Reduction of the C3 composition in the overall product mixture would also provide benefit.

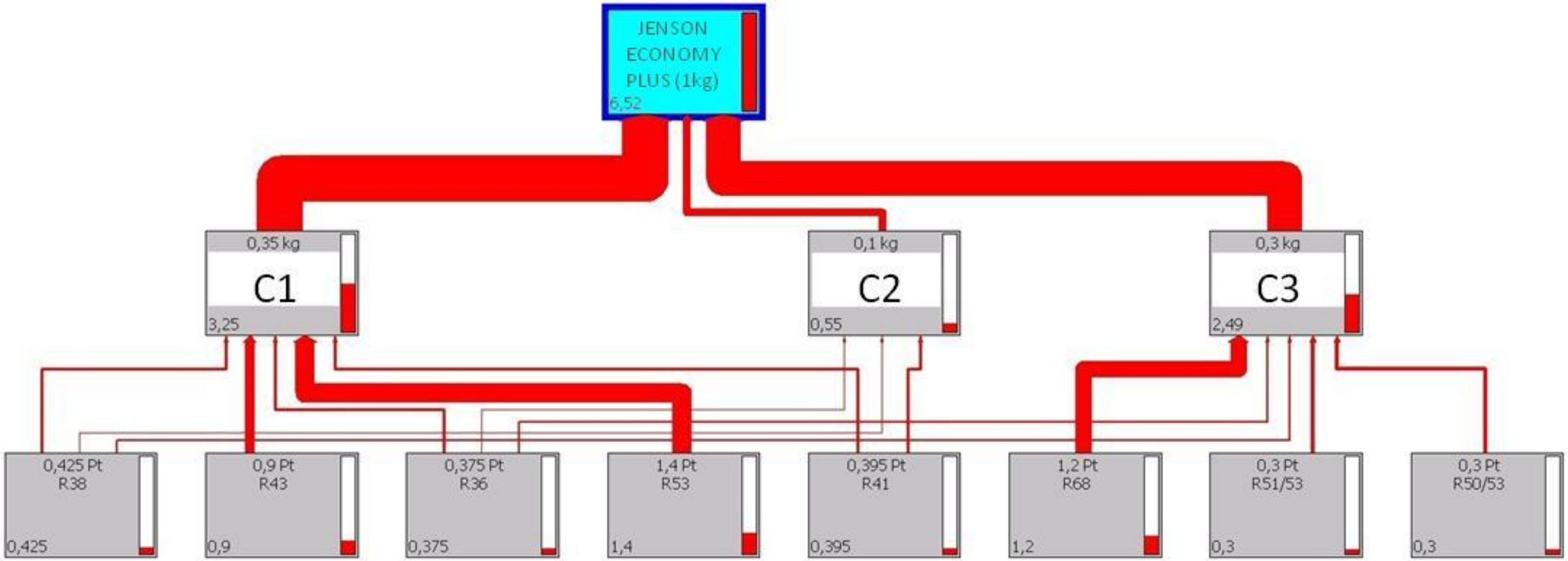

Figure 3.3: The Hazard Assessment results obtained from the Screening Tree Tool for Jenson Economy Plus.

The Screening Tree Tool enables product developers to rapidly switch from the overall Hazard Assessment figure given above (Figure 3.3) to exposure pathway based results. Results can be viewed for all of the “Characterisation” exposure pathways as well as the “Damage Assessment” indicators in Figure 3.2.

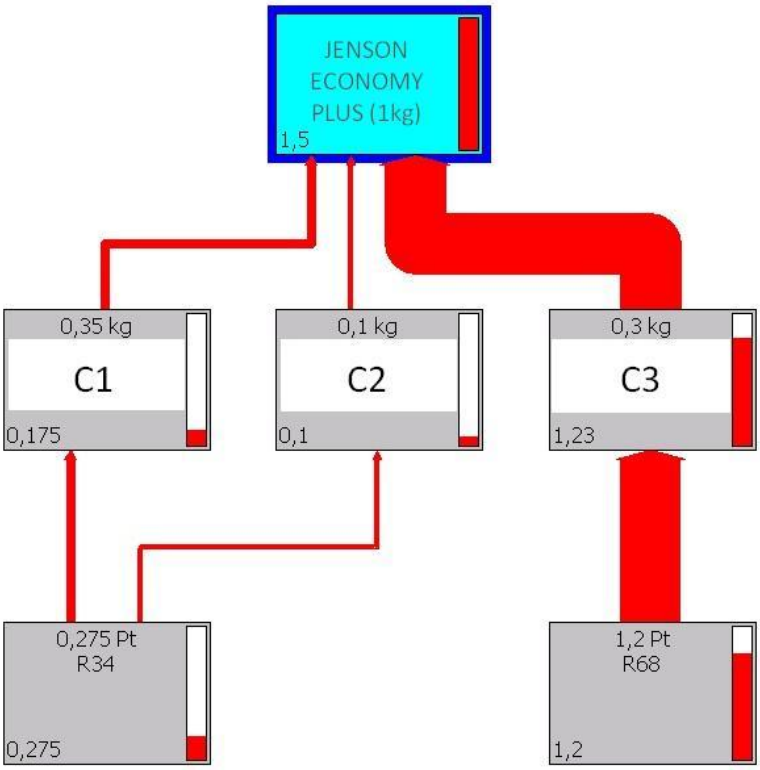

Figure 3.4: Inhalation exposure pathway results for Jenson Economy Plus.

Figure 3.4 shows the inhalation exposure pathway results for Jenson Economy Plus as one example of the exposure pathway figures that can be obtained. The Applicability Ratio for R68 for C1 is greater than 1. This implies that workers need to be protected against the risk of inhalation of this product.

The Screening Tree Tool enables the product developer to test the results (for overall hazard and specific impact pathways) quickly. This is a very efficient way of testing the chemical hazard implications of redesign/changing a product formulation. In-depth knowledge of R-phrases (for example which ones apply for environmental or human health hazard, or the severity of the hazard represented by a given R-phrase) is not required to use and interpret the results from the Screening Tree Tool. As long as the specific chemical data (R-phrases that apply and threshold limit values for labelling) are entered correctly, the product designer can experiment and screen for potential improvements.

Jenson Economy Plus is a product with a relatively simple composition. However, if the raw materials for this product consisted of several substances the structure with two tiers (one for the raw material level and one for the substance level) presented in Askham et al. (2011b) could be used. This would enable Jenson A/S to have an overview over which substances were significant for chemical hazard and also which raw materials (and therefore suppliers) were significant.

3.3 The Ecodesign Process

The product strategy and development process for which Jenson A/S has used the Strategy Tool and Screening Tree Tool can be clearly linked to the Ecodesign process (Brezet et al. 1997). The links between these tools and the Ecodesign process are shown in Figure 3.5.

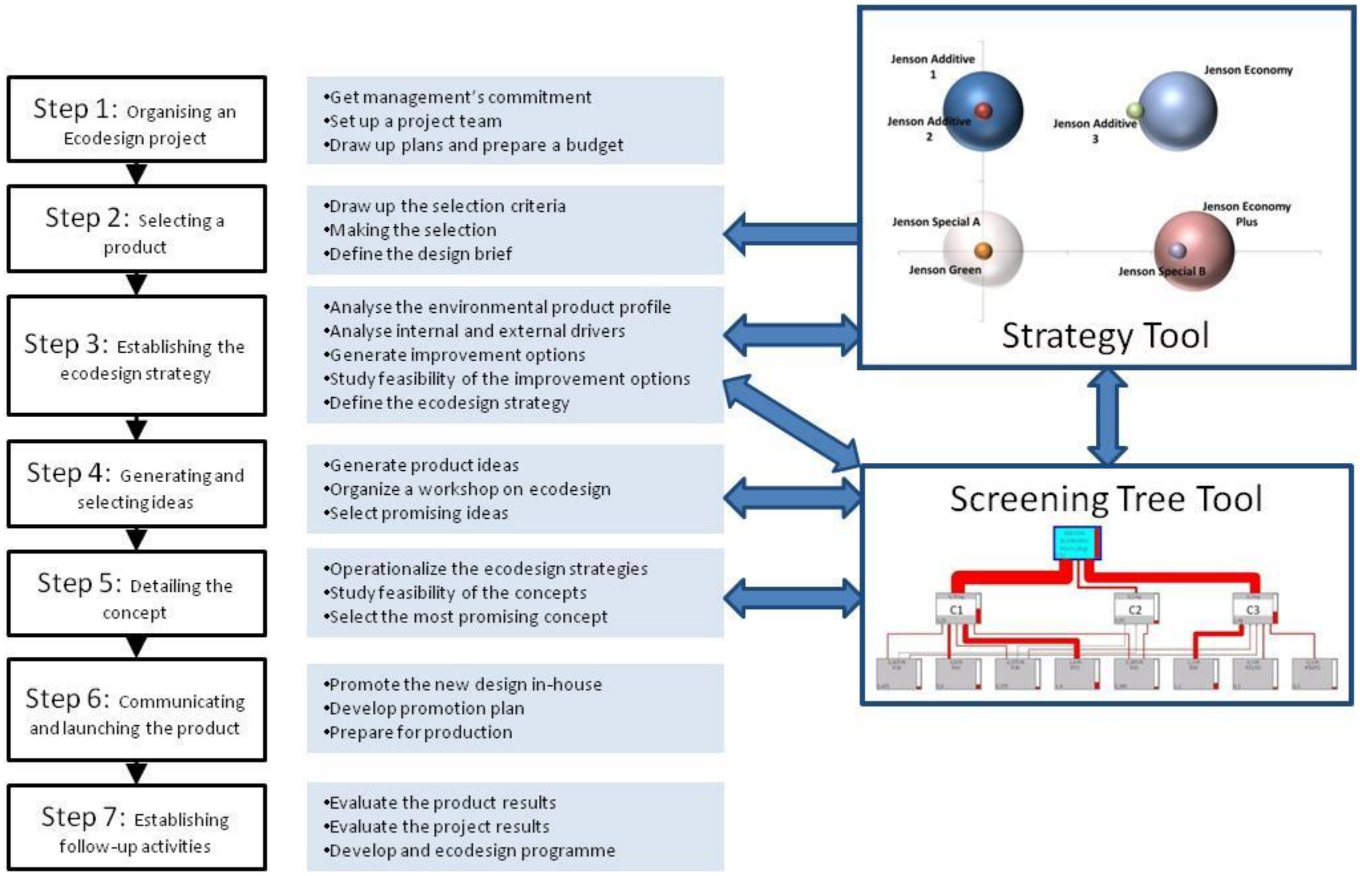

Figure 3.5: The links between the Strategy Tool, the Screening Tree Tool and the Ecodesign process.

The Strategy Tool can provide important information for decision support for Step 2 of the Ecodesign process. As exemplified above, if chemical hazards and environmental performance are important criteria for the company's market and regulatory drivers, the choice of products needing development can be made using the Strategy Tool. Environmental performance issues should be based on LCA. The Screening Tree Tool is useful for mapping the causes of the chemical hazard issues and implications of redesign/changing a product formulation. Both of these tools can provide information suitable for decision support in several steps of the Ecodesign process, as shown above. They can be actively incorporated in an iterative fashion to test the potential outcomes and feasibility of promising ideas and new concepts. This chapter clearly addresses and confirms the "red thread" for the thesis: "*It is possible to combine information from REACH with the LCA approach to develop more environmentally optimal products."*

4 Conclusions

These conclusions will address the research questions in Chapter 1.1. The first research question was: “*What are the similarities and differences between the REACH and Life Cycle Assessment (LCA) approaches, and how can synergies between these two approaches be exploited to achieve environmental improvements in a holistic perspective?*” This research question was considered in Askham (2011a). The principal differences between REACH and LCA can, to some extent, be summed up by the phrases “above threshold” as opposed to “less is better”. These perspectives, whilst seemingly at-odds, are both fundamentally geared to environmental improvements and show many parallels and synergies. The conclusions from this paper and this thesis are that combining aspects of LCA with REACH can give companies a competitive edge, and benefit society. The greater availability of toxicity data resulting from REACH can strengthen LCA toxicity assessments and methods. Potential synergies with LCA are important when implementing REACH in order to avoid suboptimal solutions and exploit the potential for innovative improvements. Many companies will use both approaches – in some cases the results will reinforce each other, but contradictions do sometimes also arise. Using both approaches will ensure that decision-makers are aware of potential conflicts during the product development process and can thus be able to seek solutions that will avoid these conflicts of interest.

“*Will the REACH approach (with a hazard risk focus) and the product functionality focus that is central to LCA be at odds with one another, resulting in different priorities for product development?*” is the second research question. This is touched upon in (Askham 2011a), and further developed with empirical examples in Askham (2011b) and Askham et al. (2011c) - the former exemplifies the substitution of an epoxy-based powder coating with a polyester-based one, and the latter examines the priorities for product development when focusing on chemical hazard indicators and/or LCA-based environmental information for eleven seating products. The powder coatings case shows how product substitution reduced the potential occupational health risk as well as environmental impacts. Thus concerns about reduction in environmental impacts being at odds with reduced occupational health risk seemed to be unfounded. In contrast, Askham et al. (2011c) provides an example of conflict. Strategic decisions about which products were most in need of product development resources were shown to be different if different environmental indicators are used as a basis for the decision. Askham et al. (2011b) also touches on this research question, as it examines whether the most significant components for chemical hazard are the same when considering individual products, or product solutions, in a life cycle perspective. This aspect of the research is not thoroughly explored, as a full LCA for the products was not performed. However, the work does indicate that the chemicals and raw materials identified as the most important for individual products were not necessarily the same when these products were combined in a two-component coating product (closer to a functional unit suitable for LCA).

“*Can REACH and LCA approaches to product development be combined to make strategic product development tools that are of use to companies?*” was the fourth research question. All of the supporting papers, and the Case Study in Chapter 3, contribute to answering this question in the affirmative. The Strategy Tool provides a direct example of REACH / LCA integration, and its practical applicability for a range of products and business sectors has been clearly demonstrated. The research has shown that the principles and practice of Ecodesign, with underpinning drivers such as energy / materials minimisation, use of recycled materials and promotion of renewable energy resources, manifest themselves in an integrated REACH / LCA approach. Specific examples of Ecodesign can be seen in the Strategy Tool's proven usefulness for the screening and benchmarking of potential new products, and the Screening Tree tool's utility in combining REACH hazardous risk information with LCA methodology, each contributing to strategic and sustainable product development.

The final research question was: "*How can REACH contribute to providing data to strengthen life cycle impact assessment models?*" Chapters 2.3 and 2.4 address the links between regulatory toxicology, REACH and LCIA. These links and the benefits to data availability and data quality as a result of REACH are discussed in Askham (2011a). It is clear that the greater availability of toxicity data resulting from REACH can generally strengthen LCA toxicity assessments and methods. The actual availability of data and what this means in practice for LCIA (both for toxicology and for fate modelling) will become clearer during the coming years. REACH is not yet fully implemented and will not be until May 2018 (Van Leeuwen et al. 2007). Thus the question remains partially open and further research will be required as the REACH implementation picture becomes clearer.

The thesis has shown that it is indeed possible to combine information from REACH with the LCA approach to develop more environmentally optimal products. There are many differences between the two approaches, as well as some similarities and synergies. The LCA approach and chemical hazard risk information can be combined to give input into Ecodesign of more environmentally optimal products. However, this must be done with knowledge of the potential conflicts and trade-offs arising. The two tools developed are examples of approaches that combine indicators from both approaches and contribute to product development. Scope for developing LCA with regard to the inclusion of hazardous substances through connecting information from LCA with information related to REACH has also been demonstrated.

5 Perspectives for Future Research

Several aspects requiring further research arose during the work on the supporting papers. These are presented here, as well as other issues that have arisen when considering the thesis work in its entirety.

The prototype Screening Tree Tool (Askham et al. 2011b) is exactly that – a prototype. It has been constructed using information from the IHS's Intelligent Authoring™ program (Atrion 2011) that Jotun uses in order to identify classification and labelling requirements. This is entered (manually) into an LCA software tool (SimaPro 7.3, PRé Consultants 2011), enabling both visualisation of chemical hazard information, and closer integration with the LCA approach. The prototype tool has illustrated how powerful this combination can be, and this thesis shows the clear links to iterative Ecodesign processes that can be achieved by use of such a tool.

The two software tools (Intelligent Authoring and SimaPro 7.3) are currently not linked and Screening Tree Tool development has relied on manual data transfer between them. Future research and collaboration possibilities in this area centre on interested users of the Tool and software developers. Collaboration of this sort was arguably under-exploited within the Innochem project. Presentation of the prototype Screening Tree Tool is likely to garner further interest from software developers. There is exciting potential for development of an Ecodesign tool that efficiently combines chemical hazard and threshold limit information with an LCA perspective. The prototype work in this thesis demonstrates the powerfulness and utility of such a decision-support tool for product development and innovation.

Askham et al. (2011b) states that the new system using H-phrases can be incorporated into the Screening Tree Tool when appropriate for the user (i.e. when the CLP directive is applicable); replacing the R-phrases the tool is currently based on. Future research could examine whether this replacement can be done with ease. Another area of potential future research associated with the Screening Tree Tool concerns the relevant R-sentences following more complex rules than the simple addition of Applicability Ratios in the current version of the tool. This is touched upon in the Screening Tree Tool paper, as it contains a case where the sum of the applicability ratios for R-phrases R20-R22 is greater than 1; this means that labelling is required. This is cited as an example of more complex labelling rules than the prototype tool is currently constructed to deal with. The mapping of the extent of these more complex labelling rules, and adaptation of the Screening Tree Tool to incorporate these, are areas for further research.

The Strategy Tool offers considerable potential for further research and development. In this tool REACH Complexity, health and environmental indicators used are given equal weight (Askham et al. 2011a). Different companies performing this type of strategic analysis may have other priorities and choose to weight these REACH aspects differently. Producers further up in the supply chain could need to have a greater emphasis on REACH Complexity, particularly as the burden for documentation lies with the producers, or importers of a given product (Commission of the European Communities, 2007). Weighting of parameters concerning human health, occupational health and the environment is a difficult area, which inevitably introduces value choices. Assigning equal value to each indicator gives them equal weight and is in itself a form of valuation. Further work on the implications and results of these value choices would strengthen the tool and clarify the degree to which weighting according to application (i.e. specific industry sector or product) is appropriate.

Broader testing of the Strategy Tool and the Screening Tree Tool and their combination (as shown in Figure 3.5) would be of interest for future research. The empirical basis for this thesis concerns use of one or both of these tools in the two participating companies. This thesis and supporting papers have centred on the development and testing of the prototype tools. This thesis concludes that they are applicable to a broad range of industry, but does not test this in more than two different companies (in two different business sectors). This does not represent an extensive test of the tools and whether they would need specific adaptations for different industry sectors, or product groups.

The current work did not combine a full LCA with the Screening Tree Tool, testing this iteratively alongside the Strategy Tool. Fully constructing the model presented in Figure 3.5 would require this. Following the use of this combination of tools in a full Ecodesign process would give valuable insight into questions such as: Does this set of tools integrate well into the Ecodesign process? In what ways is the process sensitive to industry sector and/or product type? How does company culture influence the implementation of these tools in practice? Do these tools facilitate better/more efficient Ecodesign work incorporating chemical hazard issues? All of these questions require an interdisciplinary approach, but some of them also clearly link to organisational theory and action research (Rubach 2011).

Projects incorporating Ecodesign in networks of companies could provide a good empirical basis for further research on company networks and action research aspects, as well as the links between systems engineering, Ecodesign, LCA and the two tools presented in this thesis. Askham et al. (2011c) provides some evidence that the Screening Tree Tool can be important for a company to identify areas of interest for buyer-supplier collaboration. Such use of the tools, along value-chain specific networks, could give rise to valuable research into the tools' contribution to sustainability within those value chains.

There is an aspect of the use of the Screening Tree Tool that was not foreseen, but became apparent when considering the use of this tool in screening and development of new product formulations. This could lead to both desirable and undesirable consequences. Askham et al. (2011b) shows how a product development team can use the tool to visualise which chemicals are close to the labelling limit value. This has practical value in product development, particularly in cases where there is some flexibility in the product formulation and where chemicals are just above, or just below the labelling limit. The information presented enables product developers in the lab to identify acceptable tolerances in composition for a given formulation. If they are just over a labelling limit, they can see which raw materials and chemicals contribute to this and work actively to reduce the product's R-phrase labelling requirements. This should mean real reductions in potential hazards associated with products. However, this could also mean that the tool could be used by a company to develop formulations that use combinations of substances to fulfil a function, avoiding labelling issues as far as possible, but getting close to a larger number of labelling limits. This could lead to an undesirable situation where product formulations become more complex, introducing more combined stressors for the exposed organisms. Further research is required into whether this is indeed a potential problem and whether the REACH and CLP regulations safeguard against this. This research also links with issues concerning mixture toxicity. The Innochem project includes another PhD, which is not yet complete (Gade, working title: Mixtures - verification of guidance and tools in REACH) (Hanssen 2010). Knowledge about whether a broader range of potentially hazardous effects in combination is more desirable that higher exposure to fewer types of stressors would be an important contribution to this research area.

The toxicity of mixtures and combinations of substances humans and eco-systems are exposed to are of concern. Current approaches to regulatory toxicity do not manage to include multiple stressors and exposures to substances in combination. The PhD work by Gade will address the issue of how well current models for calculating the toxicity of mixtures function in practice with empirical data from testing coatings products. This work highlights limitations and potential problems with REACH. The general field of regulatory toxicology does not manage to adequately address this issue (Van Leeuwen et al. 2007) and ecotoxicity testing does not commonly manage to incorporate testing of multiple stressors (several substances and their interaction effects) on ecosystems. This means that this is also a gap in current LCIA methods.

As REACH moves towards full implementation, further investigation of the availability of data in practice will be needed. It will be of interest to examine which information sources will be available (i.e. non-confidential), which data these will contain, and how practical implementation of these data in USEtox (or similar) can be streamlined in order to ensure LCIA models incorporate all relevant available data for substances. This work would contribute to strengthening the relevance and practicability of LCIA models – addressing significant current concerns regarding data gaps and consequent erroneous results owing to substances not effectively being treated on an equal footing. This can contribute to achieving a wider acceptance of the use of LCIA methods for toxicity in LCA. At present consensus methods (like USEtox) do not enjoy the same level of acceptance as other relative environmental indicators based on extremely complex models, such as global warming potential. The work described can also contribute to the inclusion of LCA-based indicators for toxicity in environmental product declarations (EPDs), where they are currently lacking (Abrahamsen et al. 2008).

Exposure scenario (ES) information from REACH is currently just emerging. Gade et al. (2008) was published in connection with the other PhD in the Innochem project. This documented experiences of testing the REACH draft technical guidance notes for conducting chemical safety assessments (CSA). Further publications and experience with use of the finalised technical guidance and the full implementation of REACH is likely to provide access to detailed data for ES. Empirical data and other information on ES in practice will enable further research on REACH input to the inclusion of occupational health issues in LCA. Fate factor models in LCA are also likely to benefit from the work on improving data and models applied at European level for the fate of substances in the environment. An informal collaboration with Radbound University in Nijmegen (The Netherlands) was formed during the Innochem project, concerning the issue of applying occupational exposure scenarios in REACH for intake fraction calculations in LCIA. This is an area that could be a basis for further research - examining practicable links to data arising from REACH and implementing this data in a structured fashion in LCIA, to more successfully incorporate more substance data, also occupational health issues, into LCA.

6 References

Abrahamsen U, Jørgensen R, Svendsen K, Svanes E, Fossdal (2008) Environmental Product Declarations (EPDs) as a tool for documentation/information on chemicals and toxicity in the value chains of products – a pre-study for EPD-Norge, IØT-1-2008. Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Asbjørnsen OA (1992) Systems Engineering Principles and Practices, Skarpodd, USA.

Askham C. (2011a) REACH and LCA – Methodological Approaches and Challenges. Submitted for publication. Int. J. Life Cycle Assess.

Askham C. (2011b) Environmental Product Development: Replacement of an Epoxy-Based Coating by a Polyester-Based Coating. Int. J. Life Cycle Assess, http://dx.doi.org/10.1007/s11367-011-0302-x.

Askham C, Gade AL, Hanssen OJ (2011a) Combining REACH, Environmental and Economic Performance Indicators for Strategic Sustainable Product Development. Submitted for publication. J. Cleaner Production.

Askham C, Gade AL, Hanssen OJ (2011b) Combining Chemical Risk Phrase Information with a Life Cycle Assessment Approach for Product Development. Submitted for publication. Int. J. Life Cycle Assess.

Askham C, Hanssen OJ, Gade AL, Christensen P (2011c) Strategy Tool Trial for Office Furniture, Submitted for publication. Int. J. Life Cycle Assess.

Bakshi B, Fiksel J (2003) The Quest for Sustainability: Challenges for Process Systems Engineering, AIChE Journal 49(6): 1350-1358.

Bare J, Norris G, Pennington D, McKone T (2003) TRACI-the tool for the reduction and assessment of chemical and other environmental impacts. J. Ind. Ecol 6:49-78.

Bare (2006) Risk Assessment and Life-Cycle Impact Assessment (LCIA) for Human Health Cancerous and Noncancerous Emissions: Integrated and Complementary with Consistencey within the USEPA. Hum. Ecol. Risk Assess, 12: 493-509.

Baumann H, Tillman AM (2004) The Hitch Hiker's Guide to LCA, An orientation in life cycle assessment methodology and application, Studentlitteratur, Lund, Sweden.

Behrendt S, Jasch C, Peneda MC, van Weenen H (Eds.) (1997) Life Cycle Design. A Manual for Small and Medium-Sized Enterprises. Springer, Berlin.

Brenna AB (2010) User-driven Research based Innovation (BIA). The Research Council of Norway.

http://www.forskningsradet.no/servlet/Satellite?c=Page&cid=1226993636038&p=1226993636038&pagename=bia%2FHovedsidemal. Accessed 15 March 2010.

Brezet, H., van Hemel, C., (Ed.s), 1997. Ecodesign. A Promising Approach to Sustainable Production and Consumption, first ed. United Nations Environment Programme, France.

Brown F R, Winkler J, Visita P, Dhaliwal J, Petreas M (2006) Levels of PBDEs, PCDDs, PCDFs, and coplanar PCBs in edible fish from California coastal waters. Chemosphere 64 (2): 276-286

Brundtland et al. (1987) Our Common Future. The World Commission on Environment and Development. Oxford.

Carson R (1962) Silent Spring. Penguin Classics, London.

CEFIC (2011) http://www.cefic.org/Documents/FactsAndFigures/FF%20Reports%20per%20Sections/FF_Chemical_Industry_Profie_Section.pdf Accessed 28th May 2011.

Commission of the European Communities (2007) Regulation (EC) No 1907/2006 of the European Parliament and of the council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC and 2000/21/EC. Off J Eur Union L 136 of 29.5.2007. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:136:0003:0280:EN:PDF.

Commission of the European Communities (2008) Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (1).
Off J Eur Union L 353, Volume 51, 31 December 2008.P 1-1355.
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:353:0001:1355:EN:PDF.

Council Directive 67/548/EEC of 27 June 1967 on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous components, Off J Eur Union L, 16.08.1967, 0001 – 0098.
http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexapi!prod!CELEXnumdoc&lg=EN&numdoc=31967L0548&model=guichett.

Directive 1999/45/EC of the European Parliament and of the Council of 31 May 1999 concerning the approximation of the laws, regulations and administrative provisions of the Member States relating to the classification, packaging and labelling of dangerous preparations. Off J Eur Union L 200 , 30.07.1999, 0001 – 0068.
http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexapi!prod!CELEXnumdoc&lg=en&numdoc=31999L0045&model=guichett.

Cowell SJ, Fairman R, Lofstedt RE (2002) Use of Risk Assessment and Life Cycle Assessment in Decision-Making: A common Policy Research Agenda. Risk anal 22: 879-93.

De Wit B, Meyer R (2004) Strategy: Process, Content, Context, third ed. Thomson, London.

ECHA (2008a) Guidance on information requirements and chemical safety assessment. Part E: Risk Characterisation. http://guidance.echa.europa.eu/docs/guidance_document/information_requirements_part_e_en.pdf?vers=20_08_08. Accessed 27 December 2010.

ECHA (2008b) Guidance on information requirements and chemical safety assessment. Part B: Hazard Assessment. Version 1.1. http://guidance.echa.europa.eu/docs/guidance_document/information_requirements_part_b_en.pdf?vers=20_10_08. Accessed 20 June 2011.

ECHA (2008c) Guidance on information requirements and chemical safety assessment. Part D: Exposure Scenario Building. Version 1.1. http://guidance.echa.europa.eu/docs/guidance_document/information_requirements_part_d_en.pdf. Accessed 23 June 2011.

ECHA (2009) Introductory Guidance on the CLP Regulation. http://guidance.echa.europa.eu/docs/guidance_document/clp_introductory_en.pdf. Accessed 6 June 2011.

ECHA (2010) Guidance on Information Requirements and Chemical Safety Assessment Pathfinder. http://guidance.echa.europa.eu/docs/guidance_document/information_requirements_en.htm?time=1308583161. Accessed 20 June 2011.

ECHA (2011) http://guidance.echa.europa.eu/about_reach_en.htm. Accessed 20 June 2011.

Ekvall T, Tillmann AM, Molander S (2005) Normative ethics and methodology for life cycle assessment. J. Clean. Prod. 13:1225-1234.

European Commission (2010a) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed Guidance. First edition March 2010. EUR 24708 EN. European Commission, Joint Research Centre, Institute for Environment and Sustainability. Publications Office of the European Union, Luxemburg.

European Commission (2010b) International Reference Life Cycle Data System (ILCD) Handbook – Nomenclature and other conventions. First edition 2010. EUR 24384 EN. European Commission, Joint Research Centre, Institute for Environment and Sustainability. Publications Office of the European Union, Luxemburg.

European Commission (2011) Life Cycle Thinking and Assessment website. Institute for the Environment and Sustainability, Joint Research Centre, European Commission. http://lct.jrc.ec.europa.eu/assessment/projects#d. Accessed 12 June 2011.

Fet A M, Skau EM, Haskins C (2010) A Framework for Environmental Analyses of Fish Food Production Systems Based on Systems Engineering Principles. Syst. Eng. 13(2): 109-118.

Gade AL, Øvrebø S, Hylland K (2008) Testing REACH draft technical guidance notes for conducting chemical safety assessments – The experience of a downstream user of a preparation. Regul. Toxicol. Pharmacol. 51: 168-180.

Goedkoop M, Spriensma R (2000) The Eco-Indicator 99 A damage Oriented Method for Life Cycle Impact Assessment, Methodology Annex, April 2000, second edition, Pré Consultants BV, The Netherlands.

Giudice F, La Rosa G, Risitano A (2006) Product Design for the Environment. A Life Cycle Approach. Taylor & Frances, USA.

Hanssen OJ (1993) Environmental Decision Systems: Integrated Method for Product Development, System Engineering and Life Cycle Assessment of Product Systems, Østfold Research Foundation, Working Paper. AR0993. Ostfold Research, Norway.

Hanssen OJ (1997) Sustainable Industrial Product Systems, Dr. techn. thesis, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Hanssen OJ (2010) Projects, Environmental Protection: Innochem. Ostfold Research. http://www.ostfoldforskning.no/Engelsk/prosjekt/innochem-448.aspx. Accessed 15 March 2010.

Hauschild MZ, Wenzel H (1998) Environmental Assessment of Products, Vol 2: Scientific Background. Chapman & Hall, London.

Hertwich EG, Mateles SF, Pease WS, McKone TE (2001) Human toxicity potentials for life cycle analysis and toxics release inventory risk screening. Environ. Toxicol. Chem. 20: 928-39.

Hertwich EG, Aabergb M, Singha B, Strømman AH (2008) Life-cycle Assessment of Carbon Dioxide Capture for Enhanced Oil Recovery, Chin. J. Chem. Eng., 16(3), 343-353.

Hofstetter P, Bare JC, Hammitt JK et al. (2002) Tools for the comparative analysis of alternatives: Competing or complementary perspectives? Risk Anal. 22(5): 833-51.

Hugo A, Pistikopoulos EN (2005) Environmentally conscious long-range planning and design of supply chain networks, J. of Cleaner Production, 13: 1471-1491.

Huijbregts MAJ, Rombouts LJA, Ragas AMJ, Van de Meent (2005) Human-Toxicological Effect and Damage factors of carcinogenic and non-carcinogenic chemicals for Life Cycle Impact Assessment, Integr Environ Assess Manag, 1(3):181-244

Hylland K, Erikson B, Hedstein A, Høstmark SA, Magnussen K, Odland JØ, Schulze PE, Schütz SE, Grini G (2010) Et Norge uten miljøgifter. Hvordan utslipp av miljøgifter som utgjør en trussel mot helse eller miljø kan stanses. (Official Norwegian Report: A Norway without Hazardous Substances. How emissions of hazardous substances that are a threat to health or the environment can be stopped.) NOU 2010:9. The Norwegian Ministry of the Environment, Oslo (in Norwegian).

Høibye L, Clauson-Kaas J, Wenzel H, Larsen HF, Jacobsen BN, Dalgaard O (2008) Sustainability assessment of advanced wastewater treatment technologies. Wat. Sci. Tech. 58(5): 963-968.

International Standard ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

IVL (2011). IVL takes Chemical footprint initiative. Swedish Environmental Research Institute. http://www.ivl.se/english/startpage/press/news/news/ivltakeschemicalfootprintinitiative.5.7df4c4e812d2da6a416800084625.html.

Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum RK (2003) IMPACT 2002+: a new life cycle impact assessment methodology, Int J Life Cycle Assess 8(6):324–330.

Klöpffer W (2003) Life-Cycle Based Methods for Sustainable Product Development. Int. J. Life Cycle Assess. 8(3): 157-159.

Løkke, S (2004) The Precautionary Principle and Regulation of Chemicals, PhD dissertation, Section for Technology, Environment and Society, Department of Development and Planning, Aalborg University, Denmark.

Macgregor K, Oliver IW, Harris L, Ridgway IM (2010) Persistent organic pollutants (PCB, DDT, HCH, HCB & BDE) in eels (Anguilla anguilla) in Scotland: Current levels and temporal trends. Environ. Pollution 158 (7): 2402-2411.

Modahl IS, Nyland CA, Raadahl HL, Hagemann R, Kårstad O, Torp TA (2009) LCA as an ecodesign tool for production of electricity, including carbon capture and storage - a study of a gas power plant case with post-combustion CO2 capture at Tjeldbergodden. Poster presented at the SETAC Europe 19th Annual Meeting, Gothenburg, Sweden 31/5-4/6/09 and the The 5th Trondheim Conference on CO2 Capture, Transport and Storage, 16-17 June, 2009, Trondheim Norway.

Modahl IS, Svanes E, Raadahl HL, Hagemann R, Kårstad O, Torp TA (2008) LCA of CO2 capture at Tjeldbergodden. Poster presented at the 4th TCCS conference (The Trondheim Conference on CO2 Capture, Transport and Storage), 16-17 October 2007 and the 2008 NorLCA symposium on Life Cycle Thinking (Hot Climate – Cool Thinking?), Fredrikstad, Norway 20-21 May 2008.

Norén K, Meironyté D (2000) Certain organochlorine and organobromine contaminants in Swedish human milk in perspective of past 20–30 years. Chemosphere 40: 1111–1123.

Norwegian Ministry of the Environment (2010) Press release 20.12.2010: Norway proposes to prohibit four hazardous substances in consumer products. Accessed 12 June 2010.

Oliver DW, Kelliher TP, Keegan Jr. JG (1997) Engineering Complex Systems with Models and Objects. McGraw-Hill, USA.

Olsen SI, Christensen FM, Hauschild M, Pedersen F, Larsen HF, Tørsløv J (2001) Life cycle impact assessment and risk assessment – a methodological comparison, Environ Impact Assess Rev 21:385-404.

Owens JW (1997) Life Cycle Assessment, Constraints on Moving from Inventory to Impact Assessment. J Ind. Ecol. 1(1): 37-49.

Pennington DW, Margni M, Payet J, Jolliet O (2006) Risk and regulatory hazard-based toxicological effect indicators in Life-Cycle Assessment (LCA).

PRé Consultants (2011) SimaPro 7.3.0 Amersfoort, The Netherlands, www.pre.nl.

Reap J, Roman F, Duncan S, Bras B (2008) A survey of unresolved problems in life cycle assessment, Part 2: impact assessment and interpretation, Int. J Life Cycle Assess. 13:374-388.

Rex E, Baumann H (2008) Implications of an Interpretive Understanding of LCA Practice, Bus. Strat. Environ., 17: 420-430.

Pizzol M, Christensen P, Schmidt J, Thomsen M (2010) Impacts of “metals” on human health: a comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA), J Clean Prod 19(6-7):646-656.

Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod M, Margni M, McKone TE, Payet J, Schuhmacher M, van de Meent D, Hauschild MZ (2008) USEtox - The UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in Life Cycle Impact Assessment. Int. J. Life Cycle Assess. 13:532-546.

Ruth M (1998) Mensch and Mesh, Perspectives on Industrial Ecology, J. of Ind. Ecol., 2(2): 13-22.

Rubach S (2011) Company Learning in a Network: A Dual Organization-Development (OD) Process. Doctoral thesis 2011:131, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Saling P, Kicherer A, Dittrich-Krämer B, Wittlinger R, Zombik W, Schmidt I, Schrott W, Schmidt S (2002) Eco-efficiency Analysis by BASF: The Method. Int. J. Life Cycle Assess. 7(4): 203-218.

Simchi-Levi D, Kaminsky P, Simchi-Levi, E (2003) Designing & Managing the Supply Chain. Concepts, Strategies & Case Studies. Second Edition. McGraw-Hill/Irwin, New York.

SETAC (2011) SETAC Europe Milan 2011, News and Updates. SETAC Globe 12(4): 2-3.

Tillmann AM (2000) Significance of Decision-Making for LCA Methodology. Environ. Impact Assess. Rev. 20:113-123.

UNEP (2011) UNEP website. http://www.unep.org/. Accessed 13 June 2011.

UN GHS (2005) Globally Harmonized System of Classification and Labelling of Chemicals (GHS) http://www.unece.org/trans/danger/publi/ghs/ghs_rev01/01files_e.html. Accessed 1st April 2011.

USEtox (2011) USEtoxTM The Model. http://www.usetox.com/. Accessed 12 June 2011.

Van de Meent D, Huijbregts MAJ (2005) Calculating life-cycle assessment effect factors from potentially affected fraction-based ecotoxicological response functions. Environ. Toxicol. Chem. 24(6): 1573-1578.

Van Leeuwen CJ, Vermeire TG (Eds.) (2007) Risk Assessment of Chemicals: An Introduction, 511-551. Springer, The Netherlands.

Van Zelm R, Huijbregts MAJ, Van de Meent D (2009) USES-LCA 2.0 – a global nested multi-media fate, exposure, and effects model. Int. J. Life Cycle Assess. 14(3): 282-284.

Visser W (2009) Landmarks for Sustainability. Events and initiatives that have changed our world. Cambridge University Programme for Sustainability Leadership. Greenleaf Publishing, Sheffield, UK.

Wegener Sleeswijk A, Heijungs R (2001) Risk Assessment and life-cycle assessment: Fundamentally different yet reconcilable. Greener Manag. Int. (special issue on chemical risk management) 41:7-87.

Wenzel H (1998) Application dependency of lca methodology: Key variables and their mode of influencing the method. Int. J. Life Cycle Assess. 3(5): 281-288.

Wenzel H, Hauschild M, Alting L (1997) Environmental Assessment of Products, Vol. 1: Methodology, Tools and Case Studies in Product Development. Chapman & Hall, London.

Wenzel H, Larsen HF, Clauson-Kaas J, Høibye L, Jacobsen BN (2008) Weighing environmental advantages and disadvantages of advanced wastewater treatment of micro-pollutants using environmental life cycle assessment. Wat. Sci. Tech. 57(1):27–32.

WRAP (2006) Environmental benefits of recycling. An international review of life cycle comparisons for key materials in the UK recycling sector. Waste and Resource Action Programme (WRAP), Banbury, England.

Appendices

REACH and LCA – Methodological Approaches and Challenges

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Abstract

Purpose

This paper discusses issues associated with the research question: *What are the similarities and differences between the REACH and Life Cycle Assessment (LCA) approaches, and how can synergies between these two approaches be exploited to achieve environmental improvements in a holistic perspective?*

Methods

The Innochem project (Hanssen, 2010) has been the vehicle for examining two different approaches for product improvement: REACH and LCA. Product LCAs and REACH assessments were performed on several products from each of the two main company participants, i.e. Jotun and HÅG . These companies are Downstream Users, according to the REACH definition: Jotun producing mixtures and HÅG manufacturing articles. Knowledge of the REACH and LCA aspects associated with these two types of products existed in the project team and was used in the project period (2006-2011), to compare the two approaches.

Results

This paper presents similarities and differences between REACH and LCA approaches as related to reducing impacts on the environment.

Conclusions

Combining aspects of LCA with REACH can give companies a competitive edge and benefit society. The greater availability of toxicity data that will result from REACH can strenghten LCA toxicity assessments and methods. The functional, life cycle approach and potential synergies from LCA are important when implementing REACH in companies in order to avoid suboptimal solutions and exploit the potential for achieving innovative improvements. Many companies will use both approaches, which may lead to results pointing in the same direction, or contradictory results. Using both approaches and exploiting concurrence and synergies between them, will ensure that decision-makers are aware of potential conflicts during the product development process and can thus be able to seek solutions that will avoid these conflicts of interest.

Keywords: REACH, LCA, chemicals, environmental improvements, products.

Introduction

Companies developing existing and new products in Europe today need to consider both regulatory requirements and environmental performance during their product development processes. In this paper the author will look more closely at Life Cycle Assessment (LCA) and the REACH directive, which are two different approaches aiming at improving the environmental performance of products.

ISO 14044 describes Life Cycle Assessment (LCA) as a technique for better understanding and addressing the environmental impacts associated with products and services. LCA is a standardised method that has a clear focus on the function for the user of the product or service, with the intention of minimising total impacts on the environment occurring as a result of fulfilling this function. Results from LCA studies used for product or system improvements have shown that it is not always the case that all impacts can be reduced by a given improvement option (Modahl et al. 2008, Modahl et al. 2009, WRAP 2006, Hertwich et al. 2008). There can be trade-offs between environmental impacts, e.g. reducing global warming potential, but increasing other environmental impacts like acidification or toxic impacts or vice versa (Wenzel et al. 2008, Høibye et al. 2008). These potential trade-offs highlight the need to consider product and product system changes in a holistic and functional perspective; if this need is ignored, then supposed improvements may have unintended and even counterproductive consequences.

REACH stands for Registration, Evaluation, Authorisation and Restriction of Chemicals. The REACH directive was adopted by the European Union (EU) in December 2006, and requires companies importing or producing chemicals (>1 tonnes/year) in the EU and EEA[16] regions to register these chemicals with the EU's Chemicals Agency (ECHA). The requirements of REACH are relevant for both individual substances and substances in mixtures (e.g. paint), although the registration demand is for substances only. REACH requires companies to register the substance's identity, classification and labelling, test results and proposed further tests for the substance, exposure potential to humans and different environmental compartments, and recommendations for safe use. The requirements for REACH increase with increased quantities of chemicals imported, or produced. If a company operates with quantities greater than 10 tonnes/year/producer or importer, a risk assessment ("Chemical Safety Report", CSR) is required for the substance. If a chemicals company does not comply with REACH, it cannot sell the particular products on the European market.

The requirements of REACH impose a large burden of documentation on industry and the Innochem project is part of the Norwegian work towards assisting companies in approaching the new REACH requirements and dealing with these in the most efficient manner possible. The Innochem project (Hanssen 2010) aims at turning new regulations for chemicals into a promoter of innovation instead of being a threat to research and development (R&D), innovation and production of chemicals in Norway and Europe. Innochem is a collaborative project involving companies (Jotun A/S and HÅG as) and research institutions (Ostfold Research, NIVA, UiO, NTNU and Aalborg University) financed by the Norwegian Research Council (BIA program, Brenna 2010) and participating companies. As part of the Innochem work, it is important to establish the similarities and differences in the methodological approaches used in REACH and LCA. This paper will endeavour to shed light on these issues.

The REACH Regulation

Historical developments in legislation and international cooperation leading up to the REACH regulation are well described in Løkke (2004). The Organisation for Economic Co-operation and Development (OECD) took a leading role in developing international consensus on good laboratory practice and testing procedures. This work from the 1980s has also been an important basis for the division of labour and schedules of tests that is reflected in the REACH regulation today. Growing concern about the long-term effects of chemicals meant that the desire for early warning and prevention of these unforeseen effects and the use of the precautionary principle as the basis for

[16] European Economic Area

chemicals regulation arose (Løkke 2004). Developments in occupational health regulations internationally were also important for the development of REACH, in order to minimise the adverse effects on the health of workers producing and using chemicals.

REACH entered into force on 1st June 2007 to streamline and improve the EU's former legislative framework on chemicals. REACH places the responsibility on industry to carry out chemical safety assessments and manage the risks that chemicals may pose to human health and the environment. The aims of REACH are (ECHA 2010, Van Leeuwen and Vermeire 2007): to improve the protection of human health and the environment from the risks that can be posed by chemicals; to enhance the competitiveness of the EU chemicals industry, a key sector for the economy of the EU; to promote alternative methods for the assessment of hazards of substances; and to ensure the free circulation of substances on the internal market of the EU.

Background on LCIA methods

Life Cycle Assessment is carried out in phases (ISO 14044, European Commission 2010, Baumann and Tillman 2004); goal and scope definition, inventory analysis, impact assessment and interpretation. Section 4 of this paper will refer to different Life Cycle Impact Assessment (LCIA) methods that include toxic impacts, specifically USEtox™ and ReCiPe. This section of the paper will therefore give a brief introduction to these methods and relevant references.

USEtox™ is described as a consensus model for chemical impact characterisation related to human toxicity and freshwater ecotoxicity (Rosenbaum et al. 2008) and is a result of the United Nations Environment Programme (UNEP)-Society for Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative. Pizzol et al. 2010 provides an overview figure of different existing LCIA methodologies. This overview shows that USEtox™ builds upon EcoIndicator 1999 (Goedkoop and Spriensma 2000), Impact 2002+ (Jolliet et al. 2003), EDIP 97 (Wenzel et al. 1997, Hauschild and Wenzel 1998) and TRACI (Bare et al. 2003). As described in Pizzol et al. (2010), USEtox™ is not a complete, standalone, LCIA method, as it includes only human and ecotoxicity, but it is a multimedia model that can assess both fate and exposure for a number of chemical emissions.

ReCiPe is a method that, like EcoIndicator 99, offers endpoint results for a set of environmental damages and weights results based on the decisions of a panel of experts (Wernet et al. 2010). The acronym ReCiPe is appropriate because the method provides a recipe to calculate life cycle impact category indicators; it also represents the initials of the institutes that were the main contributors: RIVM and Radboud University, CML, and PRé (Goedkoop et al. 2009). Pizzol et al. 2010 describes ReCiPe as harmonizing the two Dutch models CML2001 and Eco-Indicator 99, linking the midpoint approach in CML 2001 with the endpoint approach in EcoIndicator 99 in a consistent way. ReCiPe does this in two steps, so that the user can choose where to end their analysis (midpoint, e.g. for human toxicity kg 1,4-dichlorobenzene equivalents, or endpoint level, e.g. disability adjusted life years, DALY).

USES-LCA is a nested multi-media model for fate, exposure and effects (Huijbregts et al. 2000). The CML 2001 method was based on this model. USES-LCA was developed by adapting USES 2.0 (Uniform System for the Evaluation of Substances 2.0) to meet LCA specific demands, which are described in Huijbregts et al. 2000. As described in Van Beelen (2000), USES was developed by the National Institute of Public Health and the Environment (RIVM) in the Netherlands to evaluate the potential hazards and risks of notified substances on the basis of a specified dataset. The European Union System for the Evaluation of Substances (EUSES) was developed based on

USES 1.0 and the European Union Technical Guidance Document (EC 1996). Both USES and EUSES risk assessment systems are available in computerised form, where the user enters chemical properties and assumptions about the use of the chemical in order to obtain risk assessment data for the chemical for both man and the environment (Van Beelen 2000).

Similarities and differences between REACH and LCA

This section of the paper compares the similarities and differences between REACH and LCA approaches and also includes discussion of these, as a basis for the conclusions in the final part of the paper. For this comparison and discussion, the paper focuses on the following topics:

- Goal and scope
- Function and functional unit
- System boundaries
- Data collection (inventory)
- Impact assessment
- Interpretation and application

These topics were chosen because they highlight the differences between the two approaches, as well as the areas where the author sees the potential for synergies that could contribute to minimisation of adverse impacts from products and services. The areas focussed upon here will be an important basis for further work towards developing tools that can be efficiently exploited by companies wishing to be proactive with their product develpment work. LCA practitioners will also be familiar with the terminology used to structure this chapter, as this reflects terminology used in LCA methodology and standards.

Goal and Scope

REACH is an EU regulation based on risk assessment. Risk assessment involves gathering and evaluating data on health and or environmental effects and disease which can be caused by a chemical under specific exposure conditions. These data are based on experimental evidence of damage, injury, or disease, which is either directly applicable to the species and relevant exposure conditions, or extrapolated from relevant studies on other species and or exposure conditions (Van Leeuwen and Vermeire 2007). Whereas LCA is a standardised method for documenting the *potential* environmental impacts associated with products and services, which is used as a decision support tool. Adherence to REACH is compulsory for companies producing or importing chemicals in the EU (“No data, no market”, Article 5, Commission of the European Communities 2007). LCA is however not mandatory, but is an internationally standardised methodology which, as well as being important in its own right, is also used as a basis for Environmental Product Declarations (EPDs), Ecolabels, carbon footprint etc. Thus it does not seem obvious that these two approaches have many similarities at all. However, both approaches intend to minimise impacts on the environment. LCA has focus on products and services and includes evaluation of the potential environmental impacts associated with these (ISO 14044). Many companies will attempt to use both approaches as part of environmental analysis, and might find that the conclusions from the two approaches are sometimes contradictory.

LCA methodology is also often used by companies in order to focus on improvements for product systems (Baumann and Tillmann 2004). This is an aspect of LCA methodology that could provide positive influence on REACH implementation, by contributing to an innovative improvement perspective.

Function and functional unit

The REACH regulation applies to chemicals on a tonnage basis, whereas LCA has a functional and life cycle focus. In REACH, the "function" of a chemical is interpreted as a description of its use. By contrast, the "function" in LCA is the purpose that the product is designed to fulfil; it is then possible to calculate the amounts of materials and chemicals required (reference flows in LCA terminology). The potential hazards associated with chemicals and the amounts produced, or imported, determine the level of documentation and testing required for the REACH approval of their use by ECHA.

In LCA, the functional unit is defined as the "quantified performance of a product system for use as a reference unit" (ISO 14044). The functional unit is part of the scope of the study and provides a reference to which the input and output data are normalised. LCA approaches the environmental impacts of products and services with a clear focus on the function for the user (ISO 14044, Baumann and Tillman 2004). REACH is concerned with quantities of chemicals and their properties, independent of the amount needed to fulfil a function over a period of time. The functional approach is essential when considering substitution of a given chemical, or substance. It is possible that a substitute chemical has lower toxic impacts per kilogram, but more of it is required in order to fulfil the same function. In such cases, substituting one substance with another that seems to be less hazardous can lead to a total increase in environmental impacts throughout the life cycle, when the functional perspective is included. As long as the substitute substance is already approved for the particular use, the demand for exposure scenarios in order to fulfil REACH requirements would not be affected. If the chemical is significantly less hazardous the demand for exposure scenarios could in fact be reduced. It is therefore vital that the life cycle approach is considered together with the implications of REACH in order to ensure real improvements in the functional and holistic environmental profiles of products used in society. Without this approach, supposed improvements may be suboptimal or even counterproductive.

System boundaries

The goal and scope of the study in LCA affect the system boundaries. In LCA, system boundaries include which unit processes should be included in the study and the level of detail to which they are to be studied. This description often includes a flow diagram of the product life cycle, clearly showing which life cycle stages are included in the study (ISO 14044). The REACH regulation includes the term "life cycle" in a different context: there it refers to the life cycle of the chemical substance from manufacture and use, followed by release into the environment and its progress through the eco-system. In the toxicological information required for REACH chemical safety assessments the term life cycle is relevant in terms of the life cycle of the organisms affected by the chemical in question (e.g. developmental toxicity). In LCA, the life cycle of the product concerns the value chain of processes and logistical interactions that are needed in order to produce and use the product during its life time. For example, this could include extraction of raw materials and resources needed to produce the product, production of intermediates, production and use of the product itself (including maintenance) and its final disposal, or recycling. Ideally, LCA studies include all the relevant inputs and outputs from this value chain (e.g. electricity consumption and direct emissions) as well as the indirect resource consumption and indirect emissions associated with these inputs and outputs (e.g. emissions to air from coal power, where electricity from coal is an input to a given process in the relevant value chain). REACH does not encompass resource consumption and emissions arising from the production of chemicals. Intermediate products are only considered if they are on-site isolated intermediates, or if they are transported in quantities over one tonne or more per year (Commission of the European Communities 2007).

System boundaries in LCA also include the selection of impact categories, category indicators and characterisation models. These categories can include many different environmental impacts, such as global warming potential, ozone depletion potential and acidification potential, as well as potential toxic effects on humans and the environment. REACH is concerned with toxic impacts on humans and the environment, and does not directly include other environmental effects. However, it is interesting to note that in ECHA (2008) LCIA is given as useful in order to get an idea of likely resulting impacts “in the case several emissions not related to (eco)-toxicity have been identified”.

Data collection (inventory)

In order to perform the assessments required, experts have to quantify emissions to the environment and potential impacts on the environment and human health associated with these. Both approaches also require considerable amounts of data collection and management. If a produced product falls under REACH, the information required for general registration is detailed in Annex VI of the regulation (Commission of the European Communities 2007). This includes the following: general registrant information; identification of the substance (including physical and chemical properties); information on its manufacture and use; classification and labelling (e.g. hazard classification); guidance on safe use (including first-aid and risk management measures); and information on exposure. If a substance is manufactured or imported in quantities of 10 tonnes or more, detailed information is required, specifically toxicological information (described in Annex VIII of the regulation, e.g. skin irritation, eye irritation and mutagenicity). The level of toxicological information and the type of data required increases for chemicals produced in quantities over 100 tonnes per year (e.g. repeated dose toxicity, reproductive toxicity and ecotoxicological information, Annex IX) and also for those produced over 1000 tonnes per year (e.g. carcinogenicity, Annex X).

Release estimation for REACH environmental exposure estimation is not based on the physico-chemical properties of the substance, but the substance properties are used as an important part of the environmental exposure estimation. This is fully in line with the LCIA approach (e.g. USEtox^{TM}, Rosenbaum et al. 2008, Hauschild et al. 2008 and USES-LCA, Van Zelm et al. 2009b).

There is an equivalent process in LCIA to the process in REACH of estimating releases: this is the life cycle inventory phase, which maps the emissions released into the environment. This information is often obtained from companies and/or databases. If unknown, the REACH guidance (in its current form) recommends default parameters for derivation of the environmental release rate. A table of default values is given in regulations (Table R.16-23, ECHA 2010b), where values are given for default worst case release factors, e.g. manufacture of chemicals: 5% to air, 6% to water (before sewage treatment plant) and 0.01% to soil. The values shown in this table have been selected from general release information from EC (2003) for representative cases, but assuming there are no risk management measures in place. The distribution of the chemicals in question is not based on physico-chemical properties of a substance. The guidance describes these values as conservative.

Exposure scenarios for workers required under REACH will include intake fraction estimates. Exactly the same estimates can have direct application in LCIA human toxicity work, e.g. in the USEtox methodology CF = iF x EF, where CF [cases/$kg_{emitted}$] is the characterisation factor, iF is the intake fraction [kg_{intake}/$kg_{emitted}$] and EF is the effect factor [cases/kg_{intake}] (Hauschild et al. 2008, Rosenbaum et al. 2008 and Hellweg et al. 2009).

Implementation of REACH will lead to greater availability of toxicity data for chemicals and substances in use in Europe. This can strengthen LCA results and methodology by providing useful data for evaluation of toxic effects in a life cycle perspective. A major problem with using existing methods for toxic effects (both for humans and ecosystems) in LCA has been data availability and data quality. This is both in terms of inventory data and chemical fate and effect data regarding assessment models. An illustration of this is that SimaPro 7.3.0 (Pré Consultants 2011), a well known LCA tool, including several LCA databases, includes less than 4000 different substances that can be emitted to air and less than 3500 that can be emitted to water. The USEtox database (USEtox^{TM} 2010) includes CFs for 3073 organic and 21 inorganic substances. Uncertainties associated with models used for the evaluation of the potential human health and ecotoxicity impacts used in LCA have been discussed by many authors, some examples being Reap et al. (2008), Larsen and Hauschild (2007), Huijbregts et al. (2003), Van Zelm et al. (2006 and 2009). This issue is also addressed in the literature about the UNEP-SETAC Life Cycle Initiative consensus work (e.g. Rosenbaum et al. 2008, Hauschild et al. 2008). The increased focus on toxic effects and amounts of chemicals and substances in society should make it easier to obtain these data. In this way data arising from REACH may help to fill the gaps for chemicals and substances that do not have characterisation factors in current toxic effect models.

Thus, both REACH and LCA may benefit by exploiting information and data from each other's guidance documents and databases. One example of this is in ECHA (2008, page 75), where it is written that "LCA databases may provide average emission data related to the impacts of various materials and processes" [required for social economic analysis].

Models developed for toxic effects in LCIA (e.g. USEtox^{TM}) already use data that is in a form that can be obtained from REACH information. However, it is highly possible that many of the details needed for REACH (such as the detailed exposure assessments in the Chemical Safety Reports) will be confidential, while the results (e.g. use gloves, wear safety glasses) will be public. These results are not information that is typically useful for LCA work.

The intensified work with fate and exposure models that is a result of REACH should provide data that can give useful input in LCA fate, exposure and effect models. REACH guidance and models (e.g. ECETOC, European Centre for Ecotoxicology and Toxicology of Chemicals, ECETOC 2010) enable the user to specify an activity and risk management measures and thus obtain exposure estimate for workers. This type of information can be a powerful tool for LCA database providers, enabling faster, more standardised estimates of exposure where specific data is not available to the LCA practitioner.

Impact Assessment

Life cycle impact assessment (LCIA) is a part of the LCA process. Impacts can include toxic effects on human health and ecosystems (e.g. Rosenbaum et al. 2008). Methods for evaluation of human and environmental effects in both approaches are also based on common scientific roots, i.e. EUSES (European Union System for the Evaluation of Substances, EUSES 2010). Physical and chemical properties of the chemicals and experimental data on toxicity are central for both REACH and LCA toxicity assessments. In both cases, these properties (or effects) are combined with environmental compartment models. The degree of exposure suffered by the relevant recipients is also an important part of the calculations in both approaches. The EUSES risk assessment approach uses information on qualities of recipients, capacity and tolerance. The environmental compartment models (e.g. local, regional, global) are more detailed than those typically used in LCIA (Huijbregts et al. 2000, Van Beelen 2000), although LCIA can in theory handle local levels of detail. There are examples of LCIA approaches that manage this for impacts with localised effects, e.g. acidification and eutrophication (Seppälä et al. 2006, Potting and Hauschild 2006), but this is not the case for toxic effects using ReCiPe and USEtox™. For toxic effects, the simplification process has led to consensus, more common ground being found with less detail, between developers of different LCIA methodology for toxic effects. Hauschild et al. 2008 describes the UNEP-SETAC Life Cycle Initiative consensus process and uses a quotation from Antoine de Saint-Exupéry to illustrate this: "Perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away". The focus for the international consensus work was on which model elements contributed the most to the relative magnitude of the LCIA characterisation factors.

A methodological comparison of LCIA (with particular focus on the Danish Environmental Design of Industrial Products, EDIP, method) and risk assessment is presented in Olsen et al. (2001). This comparison was made before the REACH regulation came into force, but the methodological comparisons given here still apply. LCA seeks best estimates and average toxicity (best practice in a comparative framework) whereas conservative estimates and no-effect typically are used in (tiered) risk assessment (REACH). This principle is also reflected in the use of the predicted no effect concentration (PNEC), which is based on the no observable effect concentration (NOEC) in risk assessment, whereas LCIA methods, such as USETox and ReCiPe use the hazardous concentration at which 50% of the species is affected (HC50) based on the effect concentration (50% of the test organism is affected, EC50, Olsen et al. 2001, Larsen and Hauschild 2007). Olsen et al. (2001) suggested that risk assessment was conservative, while LCA was realistic, which is illustrated by this difference in approach to the toxicity data on which the two approaches are based.

Environmental exposure assessment in REACH is described as encompassing all of the following targets: Fresh surface water (including sediment); Marine surface water (including sediment); Terrestrial ecosystem; Top predators via the food chain (secondary poisoning); Micro-organisms in sewage treatment systems; Atmosphere – mainly considered for chemicals with a potential for ozone depletion, global warming, ozone formation in the troposphere, acidification; Man indirect, i.e. man exposed via the environment. EUSES equations are recommended for the exposure calculations for all of the above targets (ECHA 2010a). There are different LCIA methods for calculating indirect impacts on human health (Goedkoop and Spriensma 2000 and Huijbregts et al. 2005a and b), which are also often based on EUSES equations.

Environmental exposure estimation in REACH consists of the same methodological stages as in LCIA. The guidance (ECHA 2010a) describes the main steps as:

- "Estimation of the releases to air, water (either waste water and/or surface water), and soil at local and regional scale.
- Fate and distribution of the releases in environmental compartments (air, soil, surface water, sediment, biota) and sewage treatment plants;
- Calculation of exposure concentrations in / doses for, respectively:
    - Environmental compartments (...), in terms of Predicted Environmental Concentrations (PECs), at both local and regional scales, covering both direct exposure of organisms and exposure via the food chain for predators
    - Man via the environment (...) in terms of human daily intake of the substance through drinking water, fish, leaf crops, root crops, meat and dairy products, at local and regional scale".

This is in line with LCIA methods, such as USEtox™ (Rosenbaum et al. 2008, Hauschild et al. 2008, USEtox 2010), where toxicity impact score (IS_t) is calculated using the general equation $IS_t = \sum_i(CF_{ti} \times M_i)$, where M_i is the mass emitted per emission scenario *i*, CF_{ti} is the corresponding toxicity characterisation factor summed over all emission scenarios, *i*. The characterisation factor for a given chemical is a result of its physical and chemical properties combined with its toxicity and exposure calculations (e.g. EUSES equations mentioned above), (Rosenbaum et al. 2008).

The environmental exposure estimation guidance also continues with the following information: "Most of the current guidance on environmental exposure estimation has been developed mainly for organic substances. Metals and metal compounds present particularities (natural background and historical releases, speciation, adsorption/desorption behaviour, differences in bioavailability) which require specific adaptations when performing the exposure assessment." These issues are also well known in the LCIA field, e.g. Pizzol et al. (2010) and Rosenbaum et al. (2008).

The previous paragraphs show that the calculation of toxic impacts in REACH and the equivalent potential effects in LCIA correspond with each other. There is significant overlap between the theory behind the two approaches, as well as the calculation methods, which can be exploited to the advantage of companies wanting to streamline their use of resources. The calculations are used for different purposes – in LCIA, comparisons between best estimates and average toxicity, but conservative estimates in REACH – but the principles and data sources are related.

The LCA approach results in mid-point (e.g. 1,4-Dichlorobenzene equivalents), or end-point factors (e.g. DALY, Disability Adjusted Life Years), i.e. impact potentials or impact scores whereas REACH information results in advice on risk management measures (RMM). It will require a significant change in mindset for REACH analysts to present toxic effects in a life cycle framework (for example, expressed in terms of DALY). The current perspective is that complying with REACH should reduce the exposure to a level that results in no actual effects. However, the concept of acceptable risk has been accepted elsewhere (for example, in Quantitative Risk Assessment of accident hazards, Marshall and Ruhemann 2001 and Risk Management, Van Leeuwen and Vermeire 2007). Therefore, there is potential for convergence in methods of assessing potential impact.

Interpretation and application

REACH is more obviously applicable to occupational health situations, where risk assessment steps in the REACH guidelines ensure that guidance about appropriate risk management measures (e.g. personal protective equipment) are given in order to minimise potential health effects on workers, as well as the environment. Hellweg et al. (2009) summarised the work performed for the UNEP-SETAC Life Cycle Initiative by an international expert group on the integration of human indoor and outdoor exposure in LCA. This work found that the LCA approach should include a single compartment box for indoor exposure. The comparison between indoor and outdoor human exposure per unit of emission showed that for many pollutants, intake per unit of indoor emission may be several orders of magnitude higher than for outdoor emissions. This work concluded that indoor exposure should be routinely addressed within LCA and highlighted that currently this is not the case. Synergies between REACH and the Life Cycle Impact Assessment (LCIA) part of LCA could provide important methodological development to facilitate inclusion of occupational health aspects in LCA.

The combination of LCA and REACH can be used to aid companies in strategic decisions. Research linking LCA and REACH information for products, based on a functional perspective, could lead to a powerful product innovation tool. Data about these two different aspects can be used, as for traditional LCA information, to drive change and improvement (Baumann and Tillmann 2004, pp 20-21). The work performed in the Innochem project linking these two key issues (REACH and LCA) has provided valuable input to the companies' innovation processes, (Hanssen 2010) illustrating the practical value of this approach. Exemplification of linking LCA and REACH information about products, in order to drive a more optimal product innovation process, will form the basis of further work in the Innochem project and further publications from the project team. Presently this work is focussing on coatings for the furniture and offshore industries.

Conclusions

REACH and LCA approaches are by nature different in scope and framework, but focus on some of the same issues. Many companies will use both approaches, which may result in synergies but also contradictory results. This can be problematic for decision-makers in companies involved with development of new products, or redesign of existing ones. Bearing in mind the viewpoint of both approaches and therefore paying greater attention to each approach in its intended area of application, will ensure that decision-makers are aware of potential conflicts during the product development process. They may therefore be able to seek solutions that will avoid these conflicts of interest.

The greater availability of toxicity data that will result from REACH should strengthen LCA toxicity results and methods by providing more data about the toxicological effects of chemicals. This will contribute to increasing knowledge about fate and exposure models and effects, as well as easing the data availability problems when calculating characterisation factors using models like USEtox™.

The implementation of REACH could also greatly benefit from the functional approach used in LCA. A functional approach can be essential, particularly when questions about substitution arise. If REACH is implemented in companies without exploiting the functional and life cycle approach and potential synergies from LCA, this could lead to suboptimal solutions. LCA is being considered as a method that could be appropriate as part of the social economic assessment needed for the Authorisation process (Christensen et al. 2003), although the guidelines for the Authorisation process are not yet published at the present time (ECHA 2010b).

Several examples of synergies between REACH and LCA are presented in section 4 of this paper. The theory behind the calculation of toxic impacts in LCIA and REACH, as well as the calculation methods, have a lot of concurrance, which can be exploited to the advantage of companies wanting to streamline their use of resources. Data requirements for both REACH and LCA can be aided by exploiting each other’s guidance documents and databases. Thus implementation of REACH and the associated methodological guidelines can provide sources of data that can fill data gaps in LCIA and also strengthen LCIA methodology. The examples here show perhaps clearer indications of how REACH can strengthen LCIA, but further work from the Innochem project will illustrate more specifically how exploitation of the LCA approach can also strengthen REACH implementation in companies. It seems to be clear that LCA tools can be used to improve the environmental assessments required for REACH. Exploitation of REACH information together with LCA information in order to drive more optimal product development will be considered. Here, ‘optimal’ refers to several aspects, including both environmental and resource efficiency for the environment as a whole and compliance with REACH.

LCA methodology is also often used by companies to focus on improvements of product systems. This is an aspect of LCA methodology that could provide positive influence on REACH implementation, by contributing to an innovative improvement perspective. Thus combining aspects of LCA with REACH can give companies a competitive edge and benefit society.

Acknowledgements

The author gratefully acknowledges the important contributions made by the companies participating in the Innochem project: Jotun A/S and HÅG as, which have made this work possible, as well as the financial support provided by the Norwegian Research Council through the BIA program and the Confederation of Norwegian Enterprises through The Workplace Environment Fund. Thanks also to Anne Lill Gade, Ole Jørgen Hanssen and Per Christensen who have all made valuable comments to the manuscript, as well as colleagues in Ostfold Research that have been important discussion partners during this work.

References

Bare J, Norris G, Pennington D, McKone T (2003) TRACI-the tool for the reduction and assessment of chemical and other environmental impacts, J Ind Ecol 6:49-78

Baumann H, Tillman AM (2004) The Hitch Hiker's Guide to LCA, An orientation in life cycle assessment methodology and application, Studentlitteratur, Lund, Sweden

Brenna AB (2010) User-driven Research based Innovation (BIA). The Research Council of Norway. http://www.forskningsradet.no/servlet/Satellite?c=Page&cid=1226993636038&p=1226993636038&pagename=bia%2FHovedsidemal. Accessed 15 March 2010

Christensen FM, de Bruijn JHM, Hansen BG, Munn SJ, Sokull-Klüttgen B, Pedersen F (2003) Assessment Tools under the New European Union Chemicals Policy, Greenleaf Publishing, http://ecb.jrc.ec.europa.eu/documents/REACH/PUBLICATIONS/Assessment_tools_REACH040122.pdf

Commission of the European Communities (2007) Regulation (EC) No 1907/2006 of the European Parliament and of the council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC and 2000/21/EC. Off J Eur Union L 136 of 29.5.2007. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:136:0003:0280:EN:PDF

EC (1996) Technical Guidance Documents in support of Directive 93/67/EEC on risk assessment of new notified substances and Regulation (EC) No. 488/9 on risk assessment of new notified substances (Parts I, II, III and IV). EC catalogue numbers CR-48-96-001, 002, 003, 004-EN-C

EC (2003) Technical Guidance Document in support of Commission Directive 93/67/EEC on Risk Assessment for new notified substances, Commission Regulation (EC) No 1488/94 on Risk Assessment for existing substances and Directive 98/8/EC of the European Parliament and of the Council concerning the placing of biocidal products on the market

ECETOC (2010) http://www.ecetoc.org/worker-exposure-tool-user-guide. Accessed 22 March 2010

ECHA (2008) Guidance on Socio-Economic Analysis – Restrictions http://guidance.echa.europa.eu/docs/guidance_document/sea_restrictions_en.pdf. Accessed 21 October 2010

ECHA (2010) http://guidance.echa.europa.eu/about_reach_en.htm. Accessed 25 March 2010

ECHA (2010a) Guidance on information requirements and chemical safety assessment. Chapter R.16: Environmental Exposure Estimation. Version 2 May 2010. http://guidance.echa.europa.eu/docs/guidance_document/information_requirements_r16_en.pdf?vers=27_05_10. Accessed 13 May 2011

ECHA (2010b) http://guidance.echa.europa.eu/docs/guidance_document/authorisation_application_en.pdf?time=1287663487. Accessed 21 October 2010

European Commission (2010) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed Guidance. First edition March 2010. EUR 24708 EN. European Commission, Joint Research Centre, Institute for Environment and Sustainability. Publications Office of the European Union, Luxemburg

EUSES (2010) http://ecb.jrc.ec.europa.eu/euses/. Accessed 22 March 2010

Goedkoop M, Spriensma R (2000) The Eco-Indicator 99 A damage Oriented Method for Life Cycle Impact Assessment, Methodology Annex, April 2000, second edition, Pré Consultants BV, The Netherlands

Goedkoop M, Heijungs R, Huijbregts MAJ, De Shruyver A, Struijs J, Van Zelm R (2009) ReCiPe 2008-A life cycle Assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, http://www.lcia-recipe.net/. Accessed 30 March 2010

Hanssen OJ (2010) Projects, Environmental Protection: Innochem. Ostfold Research. http://www.ostfoldforskning.no/Engelsk/prosjekt/innochem-448.aspx. Accessed 15 March 2010

Hauschild MZ, Huijbregts MAJ, Jolliet O, MacLeod M, Margni M, Van de Meent D, Rosenbaum RK, McKone TE (2008) Building a Model Based on Scientific Consensus for Life Cycle Impact Assessment of Chemicals: The Search for Harmony and Parsimony, Environ Sci Technol, 42:7032–7037

Hauschild MZ, Wenzel H (1998) Environmental Assessment of products, vol 2: scientific background. Kluwer, Hingam MA, USA

Hellweg S, Demou E, Abruzzi R, Meijer A, Rosenbaum RK, Huijbregts, MAJ, McKone T (2009) Integrating Human Indoor Air Pollutant Exposure within Life Cycle Impact Assessment, Environ Sci Technol, 43(6):1670-1679

Hertwich E, et al. (2008) Life-cycle Assessment of Carbon Dioxide Capture for Enhanced Oil Recovery, Chin J Chem Eng, 16(3), 343-353

Huijbregts MAJ, Geelen LMJ, Hertwich EG, McKone TE, Van de Meent D (2005b) A comparison between the multimedia fate and exposure models CalTOX and uniform system for evaluation of substances adapted for Life-Cycle Assessment based on the population intake fraction of toxic pollutants, Environ Tox and Chem, 24(2):486-493

Huijbregts MAJ, Gulijamse W, Ragas AMJ, Reijnders L (2003) Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling, Environ Sci Technol, 37(11):2600-2608

Huijbregts MAJ, Rombouts LJA, Ragas AMJ, Van de Meent (2005a) Human-Toxicological Effect and Damage factors of carcinogenic and non-carcinogenic chemicals for Life Cycle Impact Assessment, Integr Environ Assess Manag, 1(3):181-244

Huijbregts MAJ, Thissen U, Guinee JB, Jager T, Kalf D, Van de Meent D, Ragas AMJ, Wegener Sleeswijk A, Reijnders L (2000) Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA, Chemosphere, 41(4):541-573

Høibye L, Clauson-Kaas J, Wenzel H, Larsen HF, Jacobsen BN, Dalgaard O (2008) Sustainability assessment of advanced wastewater treatment technologies, Wat Sci Tech 58(5), 963-968

International Standard ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines

Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum RK (2003) IMPACT 2002+: a new life cycle impact assessment methodology, Int J Life Cycle Assess 8(6):324–330

Larsen HF, Hauschild M (2007) Evaluation of Ecotoxicity Effect Indicators for Use in LCIA, Int J Life Cycle Assess 12(1):24–33

Løkke, S (2004) The Precautionary Principle and Regulation of Chemicals, PhD dissertation, Section for Technology, Environment and Society, Department of Development and Planning, Aalborg University, Denmark

Marshall V, Ruhemann S (2001) Fundamentals of Process Safety, IChemE, Rugby, UK

Modahl IS, Nyland CA, Raadahl HL, Hagemann R, Kårstad O, Torp TA (2009) LCA as an ecodesign tool for production of electricity, including carbon capture and storage - a study of a gas power plant case with post-combustion CO2 capture at Tjeldbergodden. Poster presented at the SETAC Europe 19th Annual Meeting, Gothenburg, Sweden 31/5-4/6/09 and the The 5th Trondheim Conference on CO2 Capture, Transport and Storage, 16-17 June, 2009, Trondheim Norway

Modahl IS, Svanes E, Raadahl HL, Hagemann R, Kårstad O, Torp TA (2008) LCA of CO2 capture at Tjeldbergodden. Poster presented at the 4th TCCS conference (The Trondheim Conference on CO2 Capture, Transport and Storage), 16-17 October 2007 and the 2008 NorLCA symposium on Life Cycle Thinking (Hot Climate – Cool Thinking?), Fredrikstad, Norway 20-21 May 2008

Olsen SI, Christensen FM, Hauschild M, Pedersen F, Larsen HF, Tørsløv J (2001) Life cycle impact assessment and risk assessment – a methodological comparison, Environ Impact Assess Rev 21:385-404

Pizzol M, Christensen P, Schmidt J, Thomsen M (2010) Impacts of “metals” on human health: a comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA), J Clean Prod 19(6-7):646-656

Potting J, Hauschild MZ (2006) Spatial Differentiation in Life Cycle Impact Assessment. A decade of method development to increase the environmental realism of LCIA, Int J Life Cycle Assess 11 (Special Issue 1):11-13

PRé Consultants (2011) SimaPro 7.3.0 Amersfoort, The Netherlands, www.pre.nl

Reap J, Roman F, Duncan S, Bras B (2008) A survey of unresolved problems in life cycle assessment, Part 2: impact assessment and interpretation, Int J Life Cycle Assess 13:374-388

Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod M, Margni M, McKone TE, Payet J, Schuhmacher M, van de Meent D, Hauschild MZ (2008) USEtox - The UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in Life Cycle Impact Assessment, Int J Life Cycle Assess 13:532-546

Seppälä J, Posch M, Johansson M, Hettelingh J-P (2006) Country-Dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator, Int J Life Cycle Assess 11(6):403–416

USEtox™ (2010) UNEP/SETAC model for the comparative assessment of chemicals released to air, water and soil and their toxic effects on the human population and ecosystems, USEtox™ 1.01, 15 February 2010

Van Beelen P (2000) The risk evaluation of difficult substances in USES 2.0 and EUSES. A decision tree for data gap filling of Kow, Koc and BCF, RIVM report 679102050, National Institute of Public Health and the Environment (RIVM), The Netherlands

Van Leeuwen CJ, Vermeire TG (eds.) (2007) Risk Assessment of Chemicals: An Introduction, 511-551. Springer, The Netherlands

Van Zelm R, Huijbregts MAJ, Harbers JV, Wintersen A, Struijs J, Posthuma L, Van de Meent D (2006) Uncertainty in msPAF-Based Ecotoxicological Effect Factors for Freshwater Ecosystems in Life Cycle Impact Assessment, Integr Environ Assess Manage 3:203-210

Van Zelm R, Huijbregts MAJ, Posthuma L, Wintersen A, Van de Meent D (2009) Pesticide ecotoxicological effect factors and their uncertainties for freshwater ecosystems, Int J Life Cycle Assess 14(1):43–51

Van Zelm R., Huijbregts MAJ, Van de Meent D (2009b) USES-LCA 2.0: a global nested multi-media fate, exposure and effects model, Int J Life Cycle Assess 14(3):282-284

Wenzel H, Hauschild M, Alting L (1997) Environmental Assessment of Products, Vol. 1: Methodology, Tools and Case Studies in Product Development, Chapman & Hall, London

Wenzel H, Larsen HF, Clauson-Kaas J, Høibye L, Jacobsen BN (2008) Weighing environmental advantages and disadvantages of advanced wastewater treatment of micro-pollutants using environmental life cycle assessment, Wat Sci Tech 57(1):27–32

Wernet G, Conradt S, Isenring HP, Jiménez-González C, Hungerbühler K (2010) Life Cycle Assessment of fine chemical production: a case study of pharmaceutical synthesis, Int J Life Cycle Assess 15:294-303

WRAP (2006) Environmental benefits of recycling. An international review of life cycle comparisons for key materials in the UK recycling sector. Waste and Resource Action Programme (WRAP), Banbury, England

Environmental Product Development: Replacement of an Epoxy-Based Coating by a Polyester-Based Coating

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Abstract

Purpose
The purpose of this study is to document and assess the environmental impacts associated with two competing powder coating solutions using current LCA methods and available data and to check whether there is a conflict between environmental performance and occupational health issues.

Methods
Data have been gathered for the manufacture and application of the two different powder coatings. The case study is a cradle-to-gate study, using retrospective data. The data were entered into the SimaPro 7.2.4 LCA software and environmental impacts calculated using IPPC 2007, CML-IA and USEtox™ classification and characterisation methods. The USEtox methods were used both with and without interim factors, and this distinction was very important for the ranking of the alternatives. The study was performed using the functional unit: *Surface treatment of the "foot-cross" of one H05 5300 office chair for 15 years (the lifetime of the chair),* where the reference flow was 172g of powder coating to fulfil this function.

Literature about the known health effects associated with chemicals in the two solutions was also consulted in order to assess whether the main concerns driving the desire to replace the epoxy-based powder coating have been addressed and improved through using the polyester-based alternative.

Results
The life cycle environmental impacts evaluated show improvements in the potential environmental impacts analysed, due to the substitute polyester-based coating. The results for human toxicity and freshwater ecotoxicity potentials are dependent on the inclusion of interim characterisation factors. Literature sources provide evidence of irritation and sensitisation effects associated with epoxy resin, but not for the polyester resin alternative.

Conclusions
Substitution of the epoxy-based coating by a polyester-based alternative reduces the occupational health risk for workers coming into contact with the powder coating. The results show that this substitution has also led to reduced potential environmental impacts: global warming, ozone depletion, photochemical oxidant creation, acidification, eutrophication, human toxicity and freshwater ecotoxicity, when the interim factors for some metals and organics are included in the USEtox calculations.

Keywords: Life cycle assessment, furniture, powder coatings, case study, USEtox

1 Introduction

The work presented in this paper was performed as part of the Innochem research project (Hanssen 2010) financed by The Norwegian Research Council (BIA program) and the companies HÅG as and Jotun A/S. The Innochem research project is a Business Innovation Arena Project called *Innovations in response to new regulations of conventional materials in a life cycle, functional and holistic perspective,* or Innochem 2006. The project aims to turn new regulations of chemicals (REACH, Commission of the European Communities 2007) into a promoter of innovation instead of being a threat to R&D, innovation and production of chemicals in Norway and Europe.

This paper presents a case study performed for HÅG, where two alternative coatings were analysed using Life Cycle Assessment (LCA). HÅG is part of Scandinavian Business Seating AS, producing seating solutions for the international business furniture market.

2 Background: Two Alternative Coatings

The coating HÅG uses for the “foot cross” part of its office chair, shown in Figure 1, must give the appearance of polished metal, but not contain environmentally harmful substances, e.g. chrome. The coating must be robust and scratch-resistant, otherwise it will begin to look worn before the rest of the chair has come to the end of its normal fifteen-year life. If a customer replaced a chair early because of this, the environmental impacts associated with the customer’s chairs would increase (more resource use, production activities etc.) and HÅG’s image as a high quality design company would be damaged.

Fig. 1 *HÅG’s H05 5300 Chair, illustrating the metal “foot cross”*

Some of HÅG’s customers have specified a requirement for purchasing, stating that products purchased cannot contain epoxy. Thus HÅG asked its coating supplier to provide an alternative to the epoxy-based powder coating that was previously used. This alternative was a polyester-based powder coating. It was not clear to HÅG whether this purchasing requirement was based on fact; it is possible that a general feeling against epoxy could have arisen from press coverage, rather than from a sound scientific basis. In order to provide a factual basis for choice, Ostfold Research

 DOI: 10.1007/s11367-011-0302-x Online First™

documented the life cycle environmental profile of the epoxy-based powder coating compared to the polyester-based alternative, as part of the Innochem project.

HÅG has a rigorous environmental policy (HÅG 2010), which requires that they produce chairs with a long life, that are made of durable and “environmentally friendly materials”. They also state in their environmental policy that they want to be able to guarantee to their users that their products do not emit harmful gases or substances. The powder coating used should not leave harmful residues that will come into contact with the consumer. The process of applying the epoxy coating was enclosed, and the heat treatment of the foot cross ensured that the coating was melted and cured and hence in an inactive form. However, there is some evidence that epoxy can be harmful for workers (West System Inc. 2008).

There is factual evidence about sensitisation of workers to epoxy (System Three 2008, Gamer et al. 2008, Crepy et al. 2006 and Peristianis et al. 1988), but HÅG has not experienced any occupational health issues with this substance at their factory in Røros, Norway (Hæskje 2008). HÅG’s powder coating process is a closed process. Worker exposure would normally occur only to the workers involved in opening the sacks of powder coating before it is charged into the silo. The powder coating is applied in a closed spray chamber, under vacuum, ensuring no further worker exposure. The workers in contact with the sacks of powder coating wear protective equipment (a fine particle filter mask, safety glasses and gloves). The powder coating process has been described as being the same for both types of powder coating used (Haugen 2008). It should also be noted that the epoxy raw material for the Jotun powder coating used by HÅG was in solid form and had a molecular weight of >1200 g/mol. Epoxy products are often split into ranges, according to molecular weight. Epoxy products with molecular weights lower than 1000 g/mol are classified as having a high risk for sensitisation. Tavakoli (2003) carried out a literature review and industry survey of the skin sensitisation effects associated with epoxy resins. This study found that lower molecular weight epoxy resin (e.g. 340 g/mol) is mainly responsible for epoxy allergy and recommends the use of higher (>900 g/mol) molecular weight epoxy resins to reduce or prevent the possibility of developing an allergy.

3 Methods and Materials

The work presented in this paper is concerned with two different types of effects, defined here as direct (occupational exposure) health effects and indirect effects on human health and the environment. These indirect effects arise as a result of emissions and resource consumption required for manufacture and use of the powder coating product. The direct health effects (for workers exposed to the powder coating product) are considered by consulting available literature, whereas the indirect effects are assessed using LCA and calculating results for the two different coating case studies. The LCA work is the main focus of this paper, but the literature search performed to ascertain whether there is evidence for the occupational health concerns is also important for HÅG. It is also of interest to see whether the change in coating can lead to a conflict between occupational health improvements and indirect environmental effects. It is possible that a trade-off situation could arise, where the improvement of one aspect, such as health effects associated with a product, could result in a worsening of other effects, such as climate change impacts.

3.1 LCA Methodology

3.1.1 Goal Definition

The goal of the LCA was to compare two products that HÅG could use to coat metal parts; documenting the change that occurred when HÅG switched from the epoxy-based powder coating to the polyester-based powder coating they currently use. The intended audience for the detailed information available from the study was HÅG and Jotun (the coatings manufacturer, which has supplied HÅG with both coatings). The LCA presented here was also performed as part of a PhD study. The results will be used by HÅG and Jotun to evaluate the success of their product development process. HÅG will also use the information in order to gauge whether the change to a polyester-based coating required by their customers resulted in a product improvement.

3.1.2 Scope Definition

The LCA approach that was used can be described as retrospective (Tillmann 2000, Ekvall et al. 2005), or attributional (European Commission 2010), and this is appropriate for Type III Environmental Declarations and Ecodesign projects (EPDs, Baumann and Tillmann 2004, European Commission 2010). The term attributional is applied to LCAs performed for systems where the data used are historical. The aim of this case study was to analyse whether the change from the epoxy-based coating to the polyester-based coating had the desired improvement effect. Thus, it is a typical case where the attributional approach (Type A situation) is appropriate (European Commission 2010). The LCA methodology used for the comparison is described further in this section of the paper.

The Function of the Product Systems and Functional Unit

The coatings must provide adequate protection for the metal parts to ensure that they do not look shabby before the seating solution has reached the end of its fifteen-year functional life in an office environment. The seating solution has a powder coating on the metal parts, which the producer confirmed was the same amount by mass for both coatings. Changing from one product to another, for environmental reasons, might be expected to introduce a trade-off, where product functionality, longevity, or other quality issues can be affected. However, quality control tests performed by Spencer (2010 a and b) show that this is not the case for this product change. The results show that the polyester-based powder coating performs at least as well as the epoxy-based coating when exposed to wear and tear.

The powder coatings producer could not produce itemised data for production of the two different powder coatings in their production facility. The allocation of environmental burdens from production between these two different powder coatings was therefore performed on a mass basis. The functional unit used for comparison of the two coatings is therefore: *Surface treatment of the “foot-cross” of one H05 5300 office chair for 15 years (the lifetime of the chair),* where the reference flow is 172g of powder coating to fulfil this function.

Product System and System Boundaries

The product system to be studied was originally a cradle-to-gate study of two seating solutions that are the same, with the exception of the coating applied to the metal parts. This is still a cradle-to-gate study, but due to the fact that the life cycles for these two seating solutions were exactly the same, except for the coatings, only the parts of the systems that were different are included in the assessment presented here. This means that the product system studied and presented here is a cradle to gate system for powder coatings applied to the metal foot-cross for the H05 5300 office chair.

 DOI: 10.1007/s11367-011-0302-x Online First™

The assessment performed was for coatings applied at HÅG's Røros factory in Norway, where the powder coatings compared are both produced by Jotun AS in Sandefjord in Norway. The raw materials suppliers for Jotun are international. As the study was retrospective, data for suppliers were used from the reference year of 2009, where this was available. Section 3.1.3 contains more information about data used, as the reality of the data quality and data availability meant that database data was used extensively.

Life Cycle Impact Assessment (LCIA) Methods and Types of Impacts

The impact indicators used for the seating solution's Environmental Product Declaration (EPD) in Norway (The Norwegian EPD Foundation, 2008) were calculated for the two seating solution cases. The impact indicators required for an EPD do not currently include toxicity impacts, but as toxicity and health impacts were the reason for the product development process in this case study, these were also calculated. The USEtox method was used for calculation of the potential human toxicity and freshwater ecotoxicity impacts (Rosenbaum et al. 2008, USEtox 2010). The basis and methods for calculation of the impacts included in the seating solution EPD are documented in Nereng and Modahl (2007), and have been verified according to the Norwegian EPD system requirements. These environmental impacts were calculated using the classification and characterisation methods of IPCC 2007 (global warming potential, IPCC 2007) and CML-IA (potential effects of ozone depletion, photochemical oxidant creation, acidification and eutrophication; CML 2010). These calculations were performed using the SimaPro 7.2.4 software.

USEtox is described as a consensus model for chemical impact characterisation related to human toxicity and freshwater ecotoxicity (Rosenbaum et al., 2008) and is a result of the UNEP-SETAC Life Cycle Initiative. This method is used to translate an emission into an impact by using substance specific characterisation factors, or comparative toxicity potentials (CTP). USEtox is not a complete, standalone, LCIA (Life Cycle Impact Assessment) method, as it includes only human and freshwater ecotoxicity impacts, but it is a multimedia model that includes fate, exposure and effects for a number of chemical emissions. The calculations presented in this paper used SimaPro's beta version of the USEtox method, imported as a CSV file (Pré Consultants, 2010). This method included the factors available in the USEtox version downloaded from the USEtox website May 17th 2010 and has two sets of characterisation factors that can be used for the LCA assessment. One included interim factors (for both metals and some organic chemicals) and the other excluded these. The notes provided in the SimaPro beta version of this method imported into the software state: "Please note that metals, which all obtain interim factors, tend to dominate all the organic substances with several orders of magnitude in most LCAs" (Pré Consultants 2010). Both sets (with and without the interim factors for metals and some organics, as these heavily influence the results) were used for calculation of the results presented in this paper. Experts working with USEtox consider it important to include metals (Hauschild 2010), even though the factors currently included in the method are interim and need more work. Although both sets of results are presented in this paper, although most weight is given to the USEtox results including metals and the reasons for this are discussed (see Section 3). It should be noted that human toxicity is presented in the results section of this paper in CTUh, which is an abbreviation for Comparative Toxic Units, human. The principle of comparative toxic units for human and aquatic ecotoxicity is described in Rosenbaum (2008); it should be noted that both the carcinogenic and non-carcinogenic effects are aggregated in the results presented in this paper.

3.1.3 Data Collection and Assumptions

The data for the analyses presented in this paper are based on the EPD for HÅG's H05 5300 chair, as previously described. However, as the powder coating for the foot cross part of the chair was the focus of attention, the author attempted to gather specific, updated data for both powder coating alternatives. Jotun produces both powder coatings, although HÅG currently use only the polyester-based coating. Both Jotun and HÅG were involved in the data collection and quality assessment processes. HÅG's powder coating facility at their Rorøs factory consumed the same amount of energy and powder coating (in weight) regardless of which type of powder coating was used (Fjerdingen 2009, Fjerdingen 2010 and Hæsje 2008). Jotun supplied Ostfold Research with detailed information about their production process for the powder coatings and their raw materials. It was not possible for Jotun to split up their data on energy consumption and emissions according to the different powder coating products produced by their facility. Thus the energy consumption, emissions and waste produced were allocated to the products on a mass basis (per kg coating product produced). Specific raw materials consumption for each powder coating was supplied by Jotun. Due to difficulties in obtaining specific data from chemical suppliers, the raw materials composition data from Jotun was used to help choose the most appropriate database data for the most relevant chemicals available in the SimaPro 7.2.4 software used for the analysis. This is in line with the common situation described in Baumann and Tillman (2004), where specific data can be provided only for processes operated by the supplier, while data from further upstream must be obtained from other sources. In the current case, the author tried to obtain specific data directly from Jotun's suppliers, but without success. The consequence of this is that the results for the differences between the two different coatings were very dependent on database data quality. It should be noted that the choice of database data was made in close collaboration with an expert group of Jotun employees who possessed in-depth knowledge of the two powder coatings, their raw materials and the chemistry involved. This group of company experts on the coatings formulations and chemistry were the critical reviewers for the raw materials data used for this LCA. No party external to the project team, or companies involved performed a critical review. Data for the specific chemical in its correct physical form (e.g. powder, rather than liquid) was preferred. Where that was unavailable, the closest option was used (e.g. specific chemical, but LCA data that did not include the final processing stage). The majority of the database data used was for the specific chemical. Recourse to non-specific chemical data was only necessary for about 3% by mass of the coatings' raw materials. All of the raw materials data used came from the EcoInvent 2.2 database (EcoInvent 2011) implemented in SimaPro 7.2.4 by Pré Consultants.

3.2. Occupational Health

The goal for the literature search on occupational health issues was to establish whether there is evidence for the occupational health concerns associated with epoxy-based powder coatings. This information was also to be used to find out whether it was possible that a trade-off situation could arise, where the improvement of direct occupational health effects associated with a product could result in a worsening of other (indirect) effects.

The ScienceDirect search engine (Elsevier 2010) was used to find literature about the known health effects of chemicals in the two competing coating solutions. Also, internet searches were carried out for relevant material safety data sheets (MSDSs) for each chemical. The literature and MSDSs found were consulted in order to assess qualitatively whether the main concerns driving the desire to replace the epoxy-based powder coating had been addressed and improved through using the polyester-based alternative. MSDSs for the specific raw materials from Jotun's suppliers were also used. Due to confidentiality issues, only the MSDSs found in the general internet search are included in the references for this paper (see Section 7).

 DOI: 10.1007/s11367-011-0302-x Online First™

4 Results and Discussion

4.1 LCA

The LCA analyses performed provided results for the environmental impact categories of several potential effects: global warming, ozone depletion, acidification, eutrophication, photochemical oxidant creation, freshwater ecotoxicity and human toxicity. Quantitative data are not shown in this paper for reasons of confidentiality. It was therefore more interesting to present the differences between Jotun's two products. The results of the comparison between the two coatings (i.e. the different raw materials) are presented in the spider diagram, Figure 2. These results for the polyester-based powder coating are shown relative to the impacts for the original epoxy-based coating.

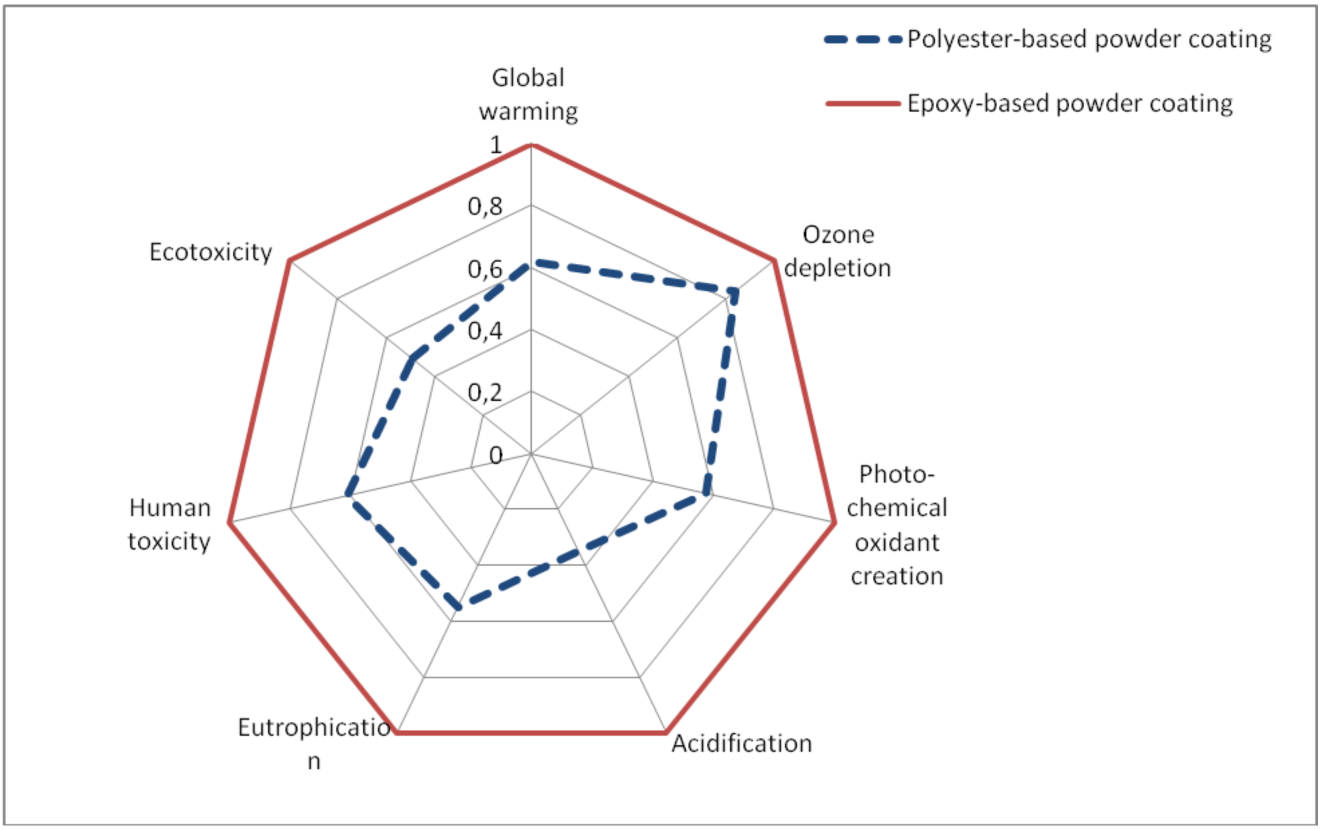

Fig. 2 *Comparison of production of the raw materials for the two different powder coatings, USEtox method including interim factors for metals*

This study does not include any form of weighting, or statistical analysis of uncertainties, so the relative importance and potential significance of the differences observed between the impact categories has not been analysed. However, Figure 2 shows that the raw materials production used for the polyester-based powder coating have lower environmental impacts for all of the impact categories analysed. The magnitudes of the impacts, in comparison to those of the alternative coating, range from approximately 35% (acidification potential) to approximately 84% (ozone depletion potential). The results for USEtox vary according to whether the interim factors for metals and some organics were included in the analysis. Without the interim factors, the difference between the two coatings changed appreciably. These results are shown in Figure 3.

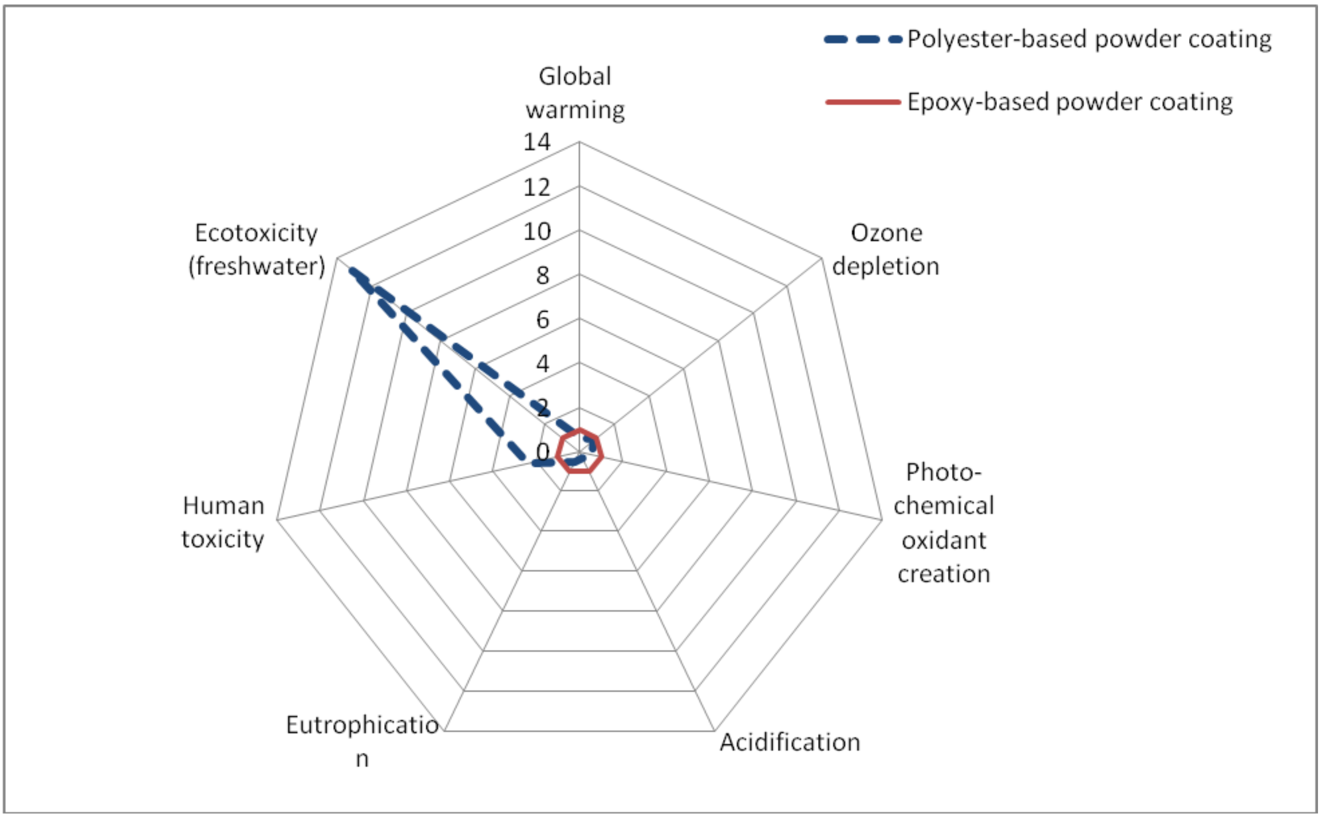

Fig. 3 *Comparison of production of the raw materials for the two different powder coatings, USEtox method not including interim factors for metals*

4.1.1 Global warming

For the epoxy-based coating the main contributions to the global warming results shown are from carbon dioxide (about 93% in Figure 2) and methane emissions to air from energy use for transport and industrial processes using fossil energy carriers. For the polyester-based system, the contributions from carbon dioxide are the most important, but dinitrogen monoxide emissions are a larger contributor (about 36%), which arise as emissions from production of chemicals.

4.1.2 Acidification

For acidification, the main contributions to the results shown in Figure 2 are a result of the emissions of nitrous oxides, sulphur dioxide and ammonia to air from fossil energy sources and petrochemical-based raw materials for chemical production.

4.1.3 Eutrophication

Nitrogen oxide emissions to air are important for eutrophication, but emissions to water are also significant. Phosphate emissions and materials causing COD (chemical oxygen demand) are the most important emissions to water (causing 31% and 13% of the impact respectively for the epoxy-based coating and 65% and 16% for the polyester-based coating). Disposal of wastes from mining (also related to fossil energy use) is an important source of these emissions. The production and use of petroleum and gas products (both for raw material and energy purposes) are important contributors for the emissions that are most important for ozone layer depletion (e.g. Halon, CFC and HCFC emissions).

4.1.4 Photochemical ozone creation

The photochemical ozone creation potential for both systems arises mainly because of emissions of NMVOC (non-methane volatile organic compounds), nitrogen oxides, sulphur dioxide and carbon monoxide. For the epoxy-based system, these emissions arise from the epoxy production

 DOI: 10.1007/s11367-011-0302-x Online First™

process, as well as fossil fuel production and use. For the polyester-based system the most important contributing processes are organic chemical production and production and use of fossil-based energy carriers.

4.1.5 USEtox-based toxic impacts

It is possible that some readers would attach less weight to the results obtained from the USEtox method that includes “interim factors”, as these may sound uncertain or flawed. However, it is recognised that data gaps that can be of importance can occur in several stages in an LCA, most notably inventory and impact assessment (Reap et al. 2008a and b). Therefore, leaving out the toxic effects of metal emissions can introduce a large data gap. The factors in the current version of USEtox consider a residence time in fresh water of no more than one year (USEtox™ 2010). The current USEtox model does not adequately include important mechanisms for the environmental fate of metals. Diamond et al. (2010) document the consensus about the need to incorporate bioavailability, speciation, size fractions and dissolution rates of metal complexes in the fate factor calculation part of the USEtox model. The bioavailability of metals can be highly influenced by transformations that they can undergo in the environment; Gandhi et al. (2011) show the importance of differences in bioavailability of metals, both on a regional and local scale. If marine ecotoxicity were to be included (with its associated longer residence time), metal emissions would be likely to be even more significant for the comparative assessment presented. Experts working with USEtox consider it important to include metals (Hauschild 2010), even though the factors currently included in the method are interim and need more work.

Considering the toxicity results without the interim factors (Figure 3), the USEtox human toxicity results are mostly a result of emissions of aldehydes, aromatic, volatile and chlorinated organic chemicals. Emissions to air are more important for carcinogenic effects from the epoxy-based system, whereas emissions to the water compartment are more important for the polyester-based system. For non-cancer human toxicity impacts, emissions to air dominate. For freshwater aquatic ecotoxicity, emissions to water dominate, with aromatic hydrocarbons and organic acids being the most important emissions. Production of organic chemicals contributes the most to freshwater ecotoxicity. Organic and chlorinated organic chemicals production, as well as production and use of energy carriers are important for potential human toxicity impacts. When the results including the interim factors for metals and some organic chemicals are included, the USEtox results change. The CTU results obtained increase by up to 4 orders of magnitude and the relative importance of specific emissions change. The potential impacts on human toxicity are dominated by disposal of residues from incineration and mining (for energy carrier production). Emissions from epoxy production are also important for the human health impacts for the epoxy system, whereas emissions from processes associated with chlorine production are of similar importance for the polyester-based system. Emissions of heavy metals to air and water dominate the contributions to potential human health impacts when the interim factors for metals are included in the USEtox assessment of both systems. The importance of heavy metal emissions for the results continues when examining the results for freshwater ecotoxicity potential for both systems. Direct emissions of heavy metals to water dominate, but deposition of heavy metals emitted to air also contributes to the potential impacts. Disposal of residues from incineration and mining (for energy carrier production) also dominate for freshwater ecotoxicity, although emissions from the burning of fossil fuels also contribute.

Excluding the interim factors for metals means that the USEtox results show a worsening in both the ecotoxicity potential and the human toxicity potential due to the change in powder coating. As previously described in the methods section of this paper (Section 3), it is desirable to include the environmental effects associated with metal emissions as far as is practicable, despite the weaknesses in the current interim factors for metals in the USEtox model. It should also be noted that prior to receiving the USEtox method beta version for SimaPro, the author performed human and ecotoxicty potential calculations using the ReCiPe method ("Europe ReCiPe H/A", i.e. European normalisation and average weighting factors, Goedkoop et al. 2009). The results from ReCiPe were similar to those presented above (in Figure 2) using USEtox with the interim factors for metals for ecotoxicity potential, i.e. an improvement was calculated for the polyester-based coating when compared to the epoxy-based coating. However, for human toxicity potential the ReCiPe calculation showed approximately the same results for both coatings. The inclusion of factors for metal emissions is important for how much (if any) improvement is calculated for human toxicity potential for emissions arising from the production of alternative raw materials for the polyester based coating. These findings are in line with the work presented in Pizzol et al. 2010 and Gloria et al. 2010 where the authors present examples and discuss the importance of characterisation factors for metals. Pizzol et al. examine nine different LCIA methods for human toxicity potential calculations, including ReCiPe and USEtox, concluding that "USEtox is recommended as the best model for LCIA on human toxicity, but mainly because of the large consensus behind it, because its uncertainties regarding metals are still high."

4.1.6 Uncertainty and Sensitivity Check

As mentioned above, this study does not include any form of weighting, or statistical analysis of uncertainties. However, a qualitative discussion of aspects that could potentially change the conclusions of this study is included here. Annex E in the ILCD handbook (European Commission 2010) gives a comprehensive overview of the types and sources of uncertainty in LCA, as applies to any LCA study. This section of the paper will elaborate on some issues that are specific to this study.

A sensitivity check has been performed for two significant choices for this study (European Commission, 2010). These significant choices are that the two coatings are equivalent in terms of function and amount applied for the given lifetime of the seating solution (15 years). When considering the results in Figure 2, it can be seen that the solutions would be equivalent if the polyester coating needed to be applied more often (had a shorter lifetime), or a larger amount was required. The change in lifetime or powder mass to give solution-equivalence depends on the environmental impact category. For this exercise the impact categories ozone depletion and acidification potential are considered, as these are the impacts that have the smallest and largest differences between the two coatings respectively. In terms of coating lifetime, if the coating functions for only 12 years, rather than 15, then the difference between the two coatings is the same for ozone depletion potential, whereas the lifetime of the coating would have to be shortened to 5 years to make the two coatings equivalent for acidification potential. Similarly, increasing the polyester coating mass from 172g to 200g (for acidification potential) or to 490g (for ozone depletion) would give equivalence between the solutions. Ostfold Research asked both HÅG and Jotun on several occasions to confirm that in practice the same mass was used for the two coatings, and both companies did so (Fjerdingen 2009, Fjerdingen 2010, Ringdal 2010, Hæsje 2008). There is a small specific gravity difference between the two coatings (0.1), which can imply that there could be a change in mass used. However, even if coating doses are in practice measured volumetrically, the slightly lower specific gravity of the polyester coating relative to the epoxy means that the mass of polyester coating is likely to be less, not greater. Spencer 2010 a and b also provide evidence that there is no reduced ability to withstand wear and tear as a result of the change in coating, so it is unlikely that a reduced coating lifetime is a real possibility.

The input data are not specific data for the given producers (see Section 3.1) and the uncertainty introduced by using non-specific data base data can be large. Database data has been used from

 DOI: 10.1007/s11367-011-0302-x Online First™

the same source, as far as possible, in order to minimise the differences in errors introduced by differing system boundaries and assumptions used in different databases.

It should also be noted that the study presented here is a cradle-to-gate study and does not include end-of-life treatment of the metal parts. The chairs are included in a take-back scheme by HÅG, but if they should be disposed of in an irresponsible fashion, then further toxic impacts could occur. Releases of chemicals or fine particles during grinding of the foot-cross of the chair could be inhaled by workers (if inadequate protective equipment was used) causing health impacts and thus affecting the conclusions of this study.

As discussed above, the use (or otherwise) of interim factors in USEtox is highly significant. The differences between Figures 2 and 3 illustrate the importance of this issue; use of interim factors changes the conclusions regarding the benefit of switching to the polyester-based coating, with respect to freshwater ecotoxicity and human toxicity.

4.2 Occupational Health

Polyester resin MSDSs available for products sold internationally (e.g. Rialtech 2006) give toxicological information about polyester resin. Rialtech 2006 states that it is “not considered to cause irritant or allergic contact dermatitis based on testing results for skin irritation (rabbit), skin sensitization (guinea pig), and clinic evaluation using repeated insult patch test”. By contrast, similar literature for epoxy resin (e.g. System Three 2008), gives health hazard information such as: “Acute: Slightly irritating to skin, moderately irritating to eyes. Odor may irritate nose, throat and respiratory tract of some persons. Chronic: May cause skin sensitization from prolonged and repeated contact”. Here it is seen that there is a sensitisation issue, which is not present for the polyester resin health hazard data.

The author also performed a search of relevant scientific literature about epoxy and polyester resins and their toxicity (using Elsevier’s ScienceDirect search engine, Elsevier 2010). Gamer et al. 2008, Crepy et al. 2006 and Peristianis et al. 1988 show experimental evidence of the sensitisation effects that can be caused by epoxy resins and chemicals that can be present in these resins. The search for research into the toxicity of polyester resin does not produce literature of a similar nature.

The literature about the health effects of occupational exposure to epoxy and polyester, described above, shows that the sensitisation and irritation aspects associated with epoxy resin are not present for the polyester alternative. Consulting the specific MSDSs for the specific suppliers of the raw materials for the two powder coating solutions largely confirmed these findings. There are components in the polyester-based coating that “may cause sensitization by skin-contact”, but these were less than 1 weight % of the polyester-based powder coating raw materials, whereas the epoxy-based powder coating had over 60 weight % of these. However, it should be noted that the molecular weight range of these epoxy components in Jotun’s powder coating is over 1200g/mol (Wasvik 2010), which is described as presenting a lower risk of sensitisation (Tavakoli et al. 2003). Thus, the literature and safety data sheet information available leads the author to conclude that the replacement of epoxy resin in the powder coating for the foot cross seems to have virtually eliminated the potential chronic health hazard of sensitisation and irritation for workers. Thus the substitution seems to be a success in terms of occupational health.

5 Conclusions

The occupational health concerns about the potential sensitisation and irritation effects arising from the use of an epoxy-based powder coating are supported by scientific evidence in literature. The substitution of an epoxy-based powder coating with a polyester-based powder coating is an improvement for occupational health effects, as it seems to have virtually eliminated the potential chronic health hazard of sensitisation for workers. There are components in the polyester-based coating that “may cause sensitization by skin-contact”, but these were less than 1 weight % of the polyester-based powder coating raw materials, whereas the epoxy-based powder coating had over 60 weight % of these.

The LCA work presented shows that substituting the epoxy-based powder coating for the polyester-based alternative reduces the potential environmental impacts analysed (global warming, ozone depletion, photochemical oxidant creation, acidification, eutrophication, ecotoxicity and human toxicity). However, the inclusion of interim factors for metals and some organics is important for how much (if any) improvement is calculated for human and freshwater ecotoxicity potential for emissions arising from the production of alternative raw materials for the polyester based coating.

In Section 4.1.6, two specific sensitivities of the calculations are tested, relating to the durability (lifetime of the seating solution) and the mass of powder coating used. Changing to the polyester coating does not lead to overall reductions in impacts if the lifespan is reduced from 15 years to 12 years or less, or the required mass of powder increases from 172g to 200g or more. However, there is no experimental or practical evidence either for lifespan reduction or for increased powder requirement.

The results presented in this paper suggest that the substitution of the epoxy-based powder coating with the polyester-based powder coating seems to be a success story. A product development change that was driven by a perceived benefit in workers’ occupational exposure has also reduced the potential life cycle environmental damage. Thus concerns about reduction in environmental impacts being at odds with reduced occupational health risk are unfounded according to the present study. These issues are not contradictory in this case, but support each other.

6 Acknowledgements

The author gratefully acknowledges the important contributions made by the companies participating in the Innochem project: Jotun A/S and HÅG as, which have made this work possible, as well as the financial support provided by the Norwegian Research Council through the BIA program. Thanks also to Anne Lill Gade, Terje Wasvik, Ole Jørgen Hanssen and Per Christensen who have all made valuable comments to the manuscript, as well as colleagues in Ostfold Research who have been important discussion partners during this work.

 DOI: 10.1007/s11367-011-0302-x Online First™

7 References

Baumann H, Tillman AM (2004) The Hitch Hiker's Guide to LCA, An orientation in life cycle assessment methodology and application, Studentlitteratur, Lund, Sweden.

CML (2010) CML-IA Characterisation Factors. http://cml.leiden.edu/software/data-cmlia.html. Accessed 27th May 2010.

Commission of the European Communities (2007) Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC and 2000/21/EC. Off J Eur Union L 136 of 29.5.2007.

Crepy MN, Jonathan AM, Pera R, Choudat D (2006) Fleuriste : une exposition professionnelle inhabituelle aux resines epoxy, Arch Mal Prof et de l'Environ 67: 639-642.

Diamond ML, Gandhi N, Adams WJ, Atherton, J, Bhavsar SP, Bulle C, Campbell PGC, Dubreuil A, Fairbrother A, Farley K, Green A, Guinée J, Hauschild MZ, Huijbregts MAJ, Humbert S, Jensen KS, Jolliet O, Margni M, McGeer JC, Peijenburg WJGM, Rosenbaum R, van de Meent D, Vijver MG (2010) The clearwater consensus: the estimation of metal hazard in fresh water, Int J LCA 15 (2): 143-147.

EcoInvent (2011) http://www.ecoinvent.org/. Accessed 14th March 2011.

Ekvall, T, Tillmann, AM, Molander, S (2005) Normative ethics and methodology for life cycle assessment, J Clean Prod 13:1225-1234.

Elsevier (2010) http://www.sciencedirect.com/. Accessed May 2010.

European Commission (2010) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed Guidance. First edition March 2010. EUR 24708 EN. European Commission, Joint Research Centre, Institute for Environment and Sustainability. Luxembourg. Publications Office of the European Union.

Fjerdingen MB (2009) Personal communication, 6th May 2009.

Fjerdingen MB (2010) Personal communication, 16th June 2010.

Gamer AO, Nies E, Vohr H-W (2008) Local lymph node assay (LLNA): Comparison of different protocols by testing skin-sensitizing epoxy resin system components, Regul Toxicol and Pharmacol 52: 290-298.

Gandhi N, Huijbregts MAJ, van de Meent D, Peijnenburg WJGM, Guinée J, Diamond ML (2011) Implications of geographic variability on Comparative Toxicity Potentials of Cu, Ni and Zn in freshwaters of Canadian ecoregions, Chemosphere (82): 268-277.

Gloria T, Russell A, Atherton J, Baker S, Cook M (2010) Ecological Toxicity Methods and Metals. An examination of two case studies, Int J LCA 11(1): 26-33.

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R (2009) ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, First edition, Report I: Characterisation. http://www.lcia-recipe.net/ Accessed 27th May 2010.

Haugen G (2008) Personal communication, 11th December 2008.

Hauschild M Z (2010) Personal communication, 13th December 2010.

Hanssen OJ (2010) Innochem, Ostfold Research. http://www.ostfoldforskning.no/prosjekt /innochem-448.aspx. Accessed 15th March 2010.

HÅG (2010) http://www.hag-uk.co.uk/about_hag/environment. Accessed 26th May 2010.

Hæskje S (2008) Personal communication, 3rd October 2008.

IPPC (2007) IPCC Fourth Assessment Report, IPCC 2007 GWP 100a V1.02, http://www.ipcc.ch/ipccreports/ar4-wg1.htm

Nereng G, Modahl IS (2007) Livsløpsdata for sitteløsninger fra HÅG - Bakgrunnsdata for miljødeklarasjon (EPD) av seks sitteløsninger (*Life cycle data for HÅG's seating solutions – Background data for environmental product decrlaration (EPD) of six seating solutions*), Ostfold Research, Norway, OR 23.07 (in Norwegian).

Peristianis GC, Doak SMA, Cole PN, Hend RW (1988) Two-year carcinogenicity study on three aromatic epoxy resins applied cutaneously to CF1 mice, Food and Chem Toxicol 26: 611-624.

Pizzol M, Christensen P, Schmidt J, Thomsen M (2010) Impacts of "metals" on human health: a comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA), J Clean Prod., in press.

Pré Consultants (2010) E-mail communication from Pre Software Support with file USEtox v1.01.CSV, 22nd November 2010.

Reap J, Roman F, Duncan S, Bras B (2008a) A survey of unresolved problems in life cycle assessment, Part 1: goal and scope and inventory analysis. Int J LCA 13:290-300.

Reap J, Roman F, Duncan S, Bras B (2008b) A survey of unresolved problems in life cycle assessment, Part 2: impact assessment and interpretation. Int J LCA 13:374-388.

Rialtech (2006) Material Safety Data Sheet Polyester fibre and resin, Performance Fibers, Inc., Virginia, USA, date of issue June 2006. http://rialtech.com/HowTos/MSDS/polyester%20msds.pdf. Accessed 26th May 2010.

Ringdal OV (2010) Personal communication, 7th June 2010.

 DOI: 10.1007/s11367-011-0302-x Online First™

Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod M, Margni M, McKone TE, Payet J, Schuhmacher M, van de Meent D, Hauschild MZ (2008) USEtox - The UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in Life Cycle Impact Assessment. Int J LCA 13:532-546.

Spencer JA (2010a) Test Report, Test no. 00-2-037, 12/11/10. Slitasjetester av ulike lakktyper (Wear and tear tests for different types of coating, Norwegian) 10 000 cycles, Scandinavian Business Seating.

Spencer JA (2010b) Test Report, Test no. 00-2-038, 16/11/10. Slitasjetester av ulike lakktyper (wear and tear tests for different types of coating, Norwegian) 100 000 cycles, Scandinavian Business Seating.

System Three (2008) Material Safety Data Sheet Epoxy resin mixture, System Three, Washington, USA, date of issue August 2008. http://www.systemthree.com/reslibrary/msds/ MSDS_SystemThree_Resin.pdf. Accessed 26th May 2010.

Tavakoli SM (2003) An assessment of skin sensitisation by the use of epoxy resin in the construction industry, Research Report 079, Health and Safety Executive, Her Majesty's Stationery Office, Norwich, UK.

Tillmann AM (2000) Significance of Decision-Making for LCA Methodology, Environ Impact Assess Rev 20:113-123.

USEtox™ (2010) UNEP/SETAC model for the comparative assessment of chemicals released to air, water and soil and their toxic effects on the human population and ecosystems, USEtox™ 1.01, 15 February 2010.

The International EPD Cooperation (2008a) General Programme Instructions for Environmental Product Declarations, Supporting Annexes. Version 1.0 2008 http://www.environdec.com/pageId.asp?id=163. Accessed 4th November 2010.

The Norwegian EPD Foundation (2008) Product Category Rules for Preparing an Environmental Product Declaration (EPD) for Product Group Seating Solution, NPCR 0003, Revised version, October 2008.

USEtox (2010) The UNEP-SETAC consensus model for life-cycle toxic impacts on human health and ecosystems. http://www.USEtox.org/ Accessed 17th May 2010.

Wasvik T (2010) Personal commnunication, 25th November 2010.

West System Inc. (2008) Material Safety Data Sheet, Epoxy resin, West System Inc., Michigan, USA, date of issue January 2005. http://www.westsystem.com/ss/assets/MSDS/MSDS105-resin.pdf. Accessed 26th May 2010.

Combining REACH, Environmental and Economic Performance Indicators for Strategic Sustainable Product Development

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Abstract

The objective of the work presented was to provide a paint production company with a tool for strategic decisions in product development that could combine environmental and economic indicators with REACH information. The tool was to be in a form that would provide visual representation of several factors that are important for the company's product development, in a form that could be incorporated into current product development processes. The paper describes the indicators used, shows visual results from the trial of the strategy matrix tool, and outlines and discusses potential limitations.

The trial was performed for six products in the company's offshore range. The tool enabled product developers to combine health, environmental and financial data to screen potential new product solutions and benchmark these against others in their portfolio. The approach is applicable to providing input into strategic decisions for the company (for example where to concentrate marketing efforts), as well as product development, facilitating the understanding of complex trade-offs between different health and environmental aspects. The products analysed were within the VOC concentration proposed by the European Directive limiting the VOC content in products (Ökopol, 2009). The products that have the lowest VOC concentrations score the highest (worst) on Total REACH Score. The trial has led to the tool being incorporated at specific "gates" (or milestones) in the company's product development process.

Working closely with relevant teams across departments to develop the strategy tool presented in this paper, ensured the tool's practical usefulness, the availability of relevant data and the applicability of the results to the company's product development processes.

Keywords
REACH, Health and Environmental indicators, Economic performance, Sustainable product development, VOC.

1 Introduction

Companies designing new or redesigning existing products in Europe today need to consider both regulatory and environmental performance requirements in their strategy development, as well as during their product development processes. Economic aspects are also very important in order for a business to achieve financially sustainable product development. This paper describes a coatings company's approach to combining threes types of indicator, i.e. regulatory, health and environmental and economic, in order to improve their strategic work towards developing more sustainable products.

The strategy matrix tool (referred to as the Strategy Tool) described in this paper is based on performance indicators described below. This tool has been developed in order for the company to obtain a strategic overview of a set of products in a given product range. This paper presents the basis for the Strategy Tool and the results from testing the tool for six products in the company's offshore range. The information obtained can be used to identify important factors requiring improvement in the company's overall product portfolio, as well as in individual products. This information can be used for providing input into strategic decisions for the company (such as where to concentrate marketing efforts), as well as product development.

The work presented here has been performed as part of the Innochem project (Hanssen 2010) Innochem is a collaborative project involving companies (Jotun and HÅG) and research institutions (Ostfold Research, NIVA and Aalborg University) financed by the Norwegian Research Council (BIA program, Brenna 2010), the Confederation of Norwegian Enterprise and participating companies.

1.1 REACH

The directive for Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) was adopted by the European Union (EU) in December 2006, and requires companies importing or producing chemicals (>1 tonnes/year) in the EU and EEA regions to register these chemicals with the EU's Chemicals Agency (ECHA). REACH requirements are relevant for both individual substances and substances in mixtures (e.g. paint), although the registration demand is for substances only. Companies manufacturing or importing substances are required to register the substance's identity, classification and labelling, test results and propose further toxicity tests for the substance, exposure potential to humans and different environmental compartments, and recommendations for safe use. The requirements for REACH increase with quantities of chemicals imported, or produced. Quantities greater than 10 tonnes/year/producer or importer mean that a risk assessment ("Chemical Safety Report", CSR) is required for the substance. If a chemicals company does not comply with REACH, it cannot sell its products in the markets of the European Union or the European Economic Area (Commission of the European Communities 2007).

REACH places the responsibility on industry to carry out chemical safety assessments and manage the risks that chemicals may pose to health and the environment. REACH entered into force on 1st June 2007 to streamline and improve the EU's former legislative framework on chemicals. The aims of REACH are (ECHA 2010, van Leeuwen and Vermeire, 2007): to improve the protection of human health and the environment from the risks that can be posed by chemicals; to enhance the competitiveness of the EU chemicals industry; to promote alternative methods for the assessment of hazards of substances; and to ensure the free circulation of substances within the internal market of the EU.

2 Material and Methods

The choice of performance indicators was made in close collaboration with the company; these indicators were then developed further and made operational by the authors. They represent product related aspects that are important for the company and cover regulatory requirements imposed by REACH, legislation for classification and labelling of substances (Council Directive 67/548/EEC) and preparations (Directive 1999/45/EC), draft directive on the limitation of emissions of volatile organic compounds (Ökopol, 2009) and financial performance. The indicators are presented in more detail below.

2.1 REACH Complexity

REACH Complexity depends on the number of exposure scenarios required. Exposure scenarios are required (Article 14, Commission of the European Communities 2007) if company products contain chemicals that meet certain criteria: they require chemical safety reports under REACH and meet the criteria for classification as dangerous, or are assessed to be a PBT (persistent, bioaccumulative and toxic) or vPvB (very persistent and very bioaccumulative), and are contained in the products above specified limits. The number of substances in the product that meet these requirements dictate how many different substance exposure scenarios will be covered for in the exposure scenario of the product. The scale for REACH Complexity is shown in Table 2.

Table 2: R-phrase hazard level classification

Hazard level	REACH guidance	COSHH	Strategy Tool model	Comments
Low		R20	R20	
		R20/21	R20/21	
		R20/21/22	R20/21/22	
		R20/22	R20/22	
		R21	R21	
		R21/22	R21/22	
		R22	R22	
	R36	R36	R36	
		R36/38	R36/38	
	R38	R38	R38	
			R50	
			R50/53	
Medium	R23	R23	R23	
		R23/24	R23/24	
		R23/24/25	R23/24/25	
		R23/25	R23/25	
	R24	R24	R24	
		R24/25	R24/25	
	R25	R25	R25	
	R34	R34	R34	

		R35		
		R36/37		
	R36/37/38	R36/37/38		
		R37		
		R37/38	R37/38	
	R40			
	R41	R41	R41	
	R43	R43	R43	ECHA 2008b, p18: "Moderate R43 skin sensitizers are allocated to the moderate hazard category on the basis that exposure to these moderate skin sensitising substances should be well-controlled."
		R48/20	R48/20	
		R48/20/21	R48/20/21	
		R48/20/21/22	R48/20/21/22	
		R48/21	R48/21	
		R48/21/22	R48/21/22	
		R48/22	R48/22	
			51/53	
			52/53	
High	R26	R26	R26	
		R26/27	R26/27	
		R26/27/28	R26/27/28	
		R26/28	R26/28	
	R27	R27	R27	
		R27/28	R27/28	
	R28	R28	R28	
	R35		R35	
		R40	R40	
	R42	R42	R42	
	R43		R43	ECHA 2008b, p18: "Extreme and strong R43 skin sensitizers are allocated to the high hazard category on the basis that exposure to such potent skin sensitising substances should be strictly contained and dermal contact avoided."
		R42/43	R42/43	
	R45	R45	R45	
	R46	R46	R46	
		R48/23	R48/23	
		R48/23/24	R48/23/24	
		R48/23/24/25	R48/23/24/25	
		R48/23/25	R48/23/25	
		R48/24	R48/24	
		R48/24/25	R48/24/25	
		R48/25	R48/25	
	R49	R49	R49	
			R50/53	
			R53	
		R60	R60	

	R61	R61	
	R62	R62	
	R63	R63	
R64		R64	
R68		R68	

2.2 Health and Environmental risk

The health and environmental risks associated with the products were expressed by two indicators called “environmental class” and “health hazard class”. “Environmental class” is based upon the risk phrases (R-phrases) for effects on the environment associated with chemicals in line with European hazard labelling directives (Council Directive 67/548/EEC, Directive 1999/45/EC). It should be noted that R-phrases are to be replaced by a new system defined in the CLP (classification, labelling and packaging) directive, which has been adopted for pure substances by 01.12.2010 and will be adopted for products by 01.12.2015 (CLP regulation, Commission of the European Communities, 2008). CLP uses hazard phrases (H-phrases), rather than R-phrases, introducing the new EU system for classifying and labelling chemicals, based on the United Nations’ Globally Harmonised System (UN GHS, 2005). Annex VI (Table 3.1, Commission of the European Communities, 2008) gives harmonised classification and labelling lists, whereas Annex VII (Table 1.1, Commission of the European Communities, 2008) provides a translation from the R-phrases given in directives 67/548 and 1999/45 to the new CLP H-phrases. Thus, it will be possible to translate the tool indicators into H-phrases in the future. “Health hazard class” is based upon the R-phrases for human health. This indicator is also affected by the future adoption of CLP for mixtures of substances (as described for “environmental class” above).

The R-phrases used for the “environmental class” and “health hazard class” are grouped into three risk categories: low, medium and high. Table 1 shows which R-phrases are grouped into which category for these indicators. These risk categories are used for R-phrases in Table E.3-1 REACH CSA guidance (ECHA 2008b). However, the REACH guidance also refers to COSHH Essentials (ECHA 2008a) as an alternative source of information to compile risk management measures and operational conditions for exposure scenarios under REACH. COSHH Essentials uses a banding approach where hazards are banded (divided into hazard groups) based upon the hazard represented by the R-phrases. As many of the R-phrases are not listed in ECHA 2008b, COSHH (HSE1999) was consulted to fill in these gaps. On closer examination of the information about risk categorization for R-phrases in COSHH, some of the REACH and COSHH categories did not concur. This can be seen clearly in Table 1 (e.g. R37). Where there was a discrepancy between these two lists, the worst case scenario was assumed, thus the list in the “Strategy Tool model” column is the basis for this work. The risk phrases that are associated with environmental hazard classification are not grouped and rated by REACH or COSHH Essentials. These are grouped by experts in the paint company, based on the severity of the R-phrases (based, to some extent, on recommendations in Appendix 1, Cefic and DUCC 2009) and are shaded, in order to distinguish easily between the risk phrases associated with the health and environmental hazards.

Table 1: Scoring system for number of substances with exposure scenarios in the product.

Number of exposure scenarios required	Score
0	0
1-2	1
3-5	5
>5	10

Saling et al. (2002) uses R-phrases and hazard symbols as the basis for their logarithmic scoring system (values of 1, 10, 100 or 1000 assigned depending on the level of hazard) and state that in future the assessment base can be “formed directly from R-phrases, which can be linked to assessment numbers”. In this Strategy Tool the R-phrases hazard level classifications are weighted with low, medium and high hazard levels being assigned the values 1, 3 and 10 respectively. This weighting is the result of an expert weighting assessment by the company (Jotun). The experts have judged very toxic, toxic by prolonged exposure, sensitization and CMR effects as so severe that they are weighted as 10 in proportion to toxic, harmful and irritating (weight 3) and harmful, irritating (weight 1).

2.3 VOC Concentration

The European Parliament and The Council Of The European Union (2004) states that “the VOC content of paints, varnishes and vehicle refinishing products gives rise to significant emissions of VOCs into the air, which contribute to the local and transboundary formation of photochemical oxidants in the boundary layer of the troposphere” and that “the VOC content of certain paints and varnishes and vehicle refinishing products should therefore be reduced as much as is technically and economically feasible taking into account climatic conditions.” Content limits for the type of coating products included in this strategic work are not set in this directive. Draft proposals are however under development for inclusion in the VOC Directive (Ökopol, 2009), and customer demands for low VOC paint have for a long time been a driving force for paint product development. VOC concentration (g/l) is therefore one of the environmental criteria used for this strategy model. No score is assigned to this indicator; the actual concentration data in g/l are used.

2.4 Economic Indicator

The economic indicator is meant to represent the economic importance of the product in the product range. There are alternatives for economic indicators that could be used; the most commonly used are annual turnover and net profit (De Wit and Meyer 2004, Hanssen 1996). Brezet et al. (1997) proposes using the estimated market potential and the desired future contribution of the product towards the company’s trading results. However, some of the products included in this strategy work were new products under development that did not have available market price data or estimates of market potential, which meant that other types of indicator had to be used in this context. Raw material cost data for the different raw materials that are used to make the product was considered a reliable indicator of Jotun’s cost levels for producing these new products. Raw materials cost data was also considered to be an important economic factor for Jotun when comparing new and existing products. Thus raw materials cost data was used as the economic indicator in the model.

3 Results

A strategy tool was developed based on the indicators described above. This was in the form of an Excel spreadsheet that uses the data entered by the company to calculate the different indicators described and combined these to provide the graphical representations of product performance shown here. There are six products included in the analyses presented here. The results are presented for individual products (Products 1 to 6) and also for the products in their blended form, as each of the six individual products is actually sold as a component in a two-component coating system. The customer buys a specified blend ratio of the two components to make product X, Y or Z.

Figures 1 to 4 include scales labelled “Total REACH, Health and Environment Score” (referred to in the text in this paper as REACH Score), which is the sum of the REACH related indicators (REACH Complexity, health hazard and environmental hazard). The values obtained for each of these indicators are summed in order to calculate the total REACH, health and environment score.

The size of the spheres presented in Figure 1 represents the economic indicator (raw materials’ cost data). Thus Product 4 has the most expensive raw materials, but a very low VOC concentration. Product 1 has low raw materials costs, but a high VOC concentration and a high REACH Score. The red line indicates the authorities’ proposed VOC limit for this type of product (Ökopol, 2009).

The products presented here are sold to the customer as two component solutions, where the customer mixes the two components on site before application. This means that, when considering product function, it is also relevant to combine the relevant components to show the mixed product system, as would be applied by the customer. In Figure 2, the indicators for the two-component products are weighted according to the mass fractions of the individual components in the mixture.

This figure shows that the product with the lowest raw materials cost has the worst performance for the VOC indicator. Product X is also not much better than Product Y for Total REACH score. Product Z is better than Product Y for the REACH indicators, but not for VOC concentration. However, Product Z is still well below the legal limit for VOC concentration for these types of products (250 g/l, see the red line in Figure 1).

In order to understand the factors contributing to the x-axis value (Total REACH Score) for the products shown in Figures 1 and 2, the strategy tool also includes Figures 3 and 4. These Figures illustrate the total REACH Score, decoupling the individual contributory indicators - presenting the user with the background information for this indicator in various forms.

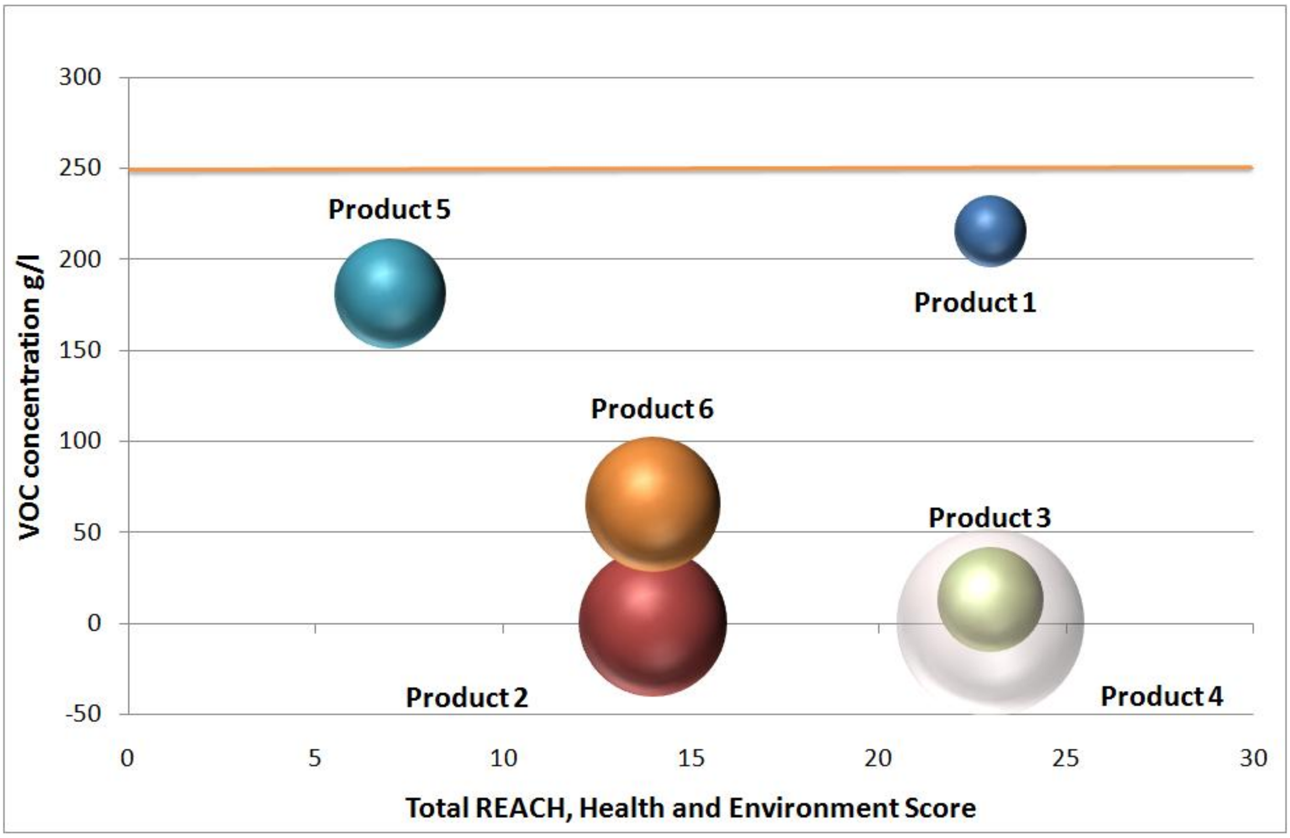

Fig. 1 *Combining Economic data with the REACH Score and VOC Concentration for Coatings Products 1-6.*

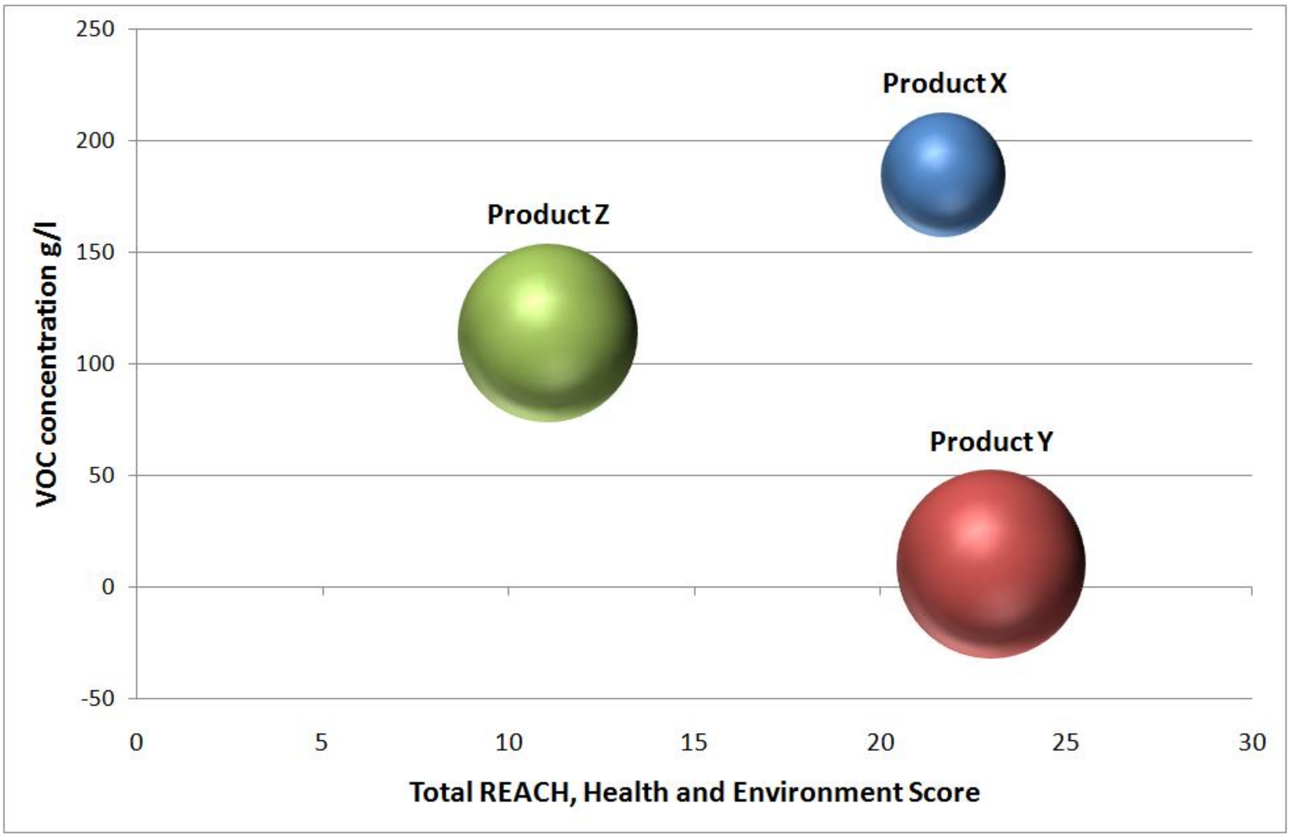

Fig. 2 *Economic, REACH Score and VOC Concentration Indicators for Two-Component Products X, Y, and Z.*

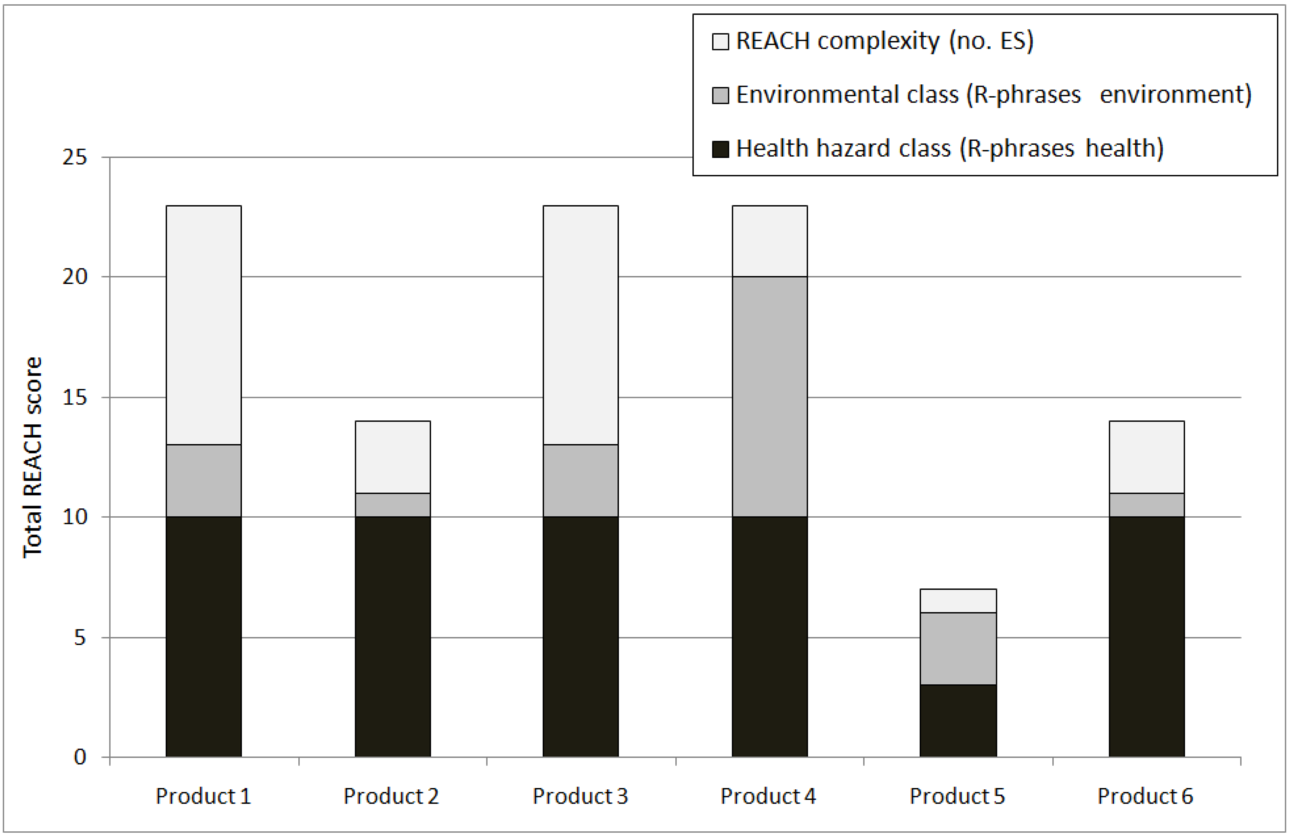

Fig. 3 *REACH Complexity, environmental hazard and health hazard for Products 1-6.*

Figure 3 shows that the score obtained for the human health hazard indicator is the same for Products 1-4 and 6. The REACH Complexity score is greatest for Products 1 and 3, whereas the high REACH score for Product 4 is due to R-phrases indicating that the product has a greater potential hazard to the environment, as well as human health. Products 2 and 6 have the lowest environmental classification. Figure 3 also shows that Product 5 has the lowest REACH score, which is a result of the lowest scores for health hazard and REACH Complexity (needing few exposure scenarios).

As previously, Figure 4 uses weighted contributions from individual components in a two-component mixture. The difference between Product X and Product Y is mainly due to environmental hazard information, whereas Product Z performs better than both of the other products for all of the indicators included in Figure 4.

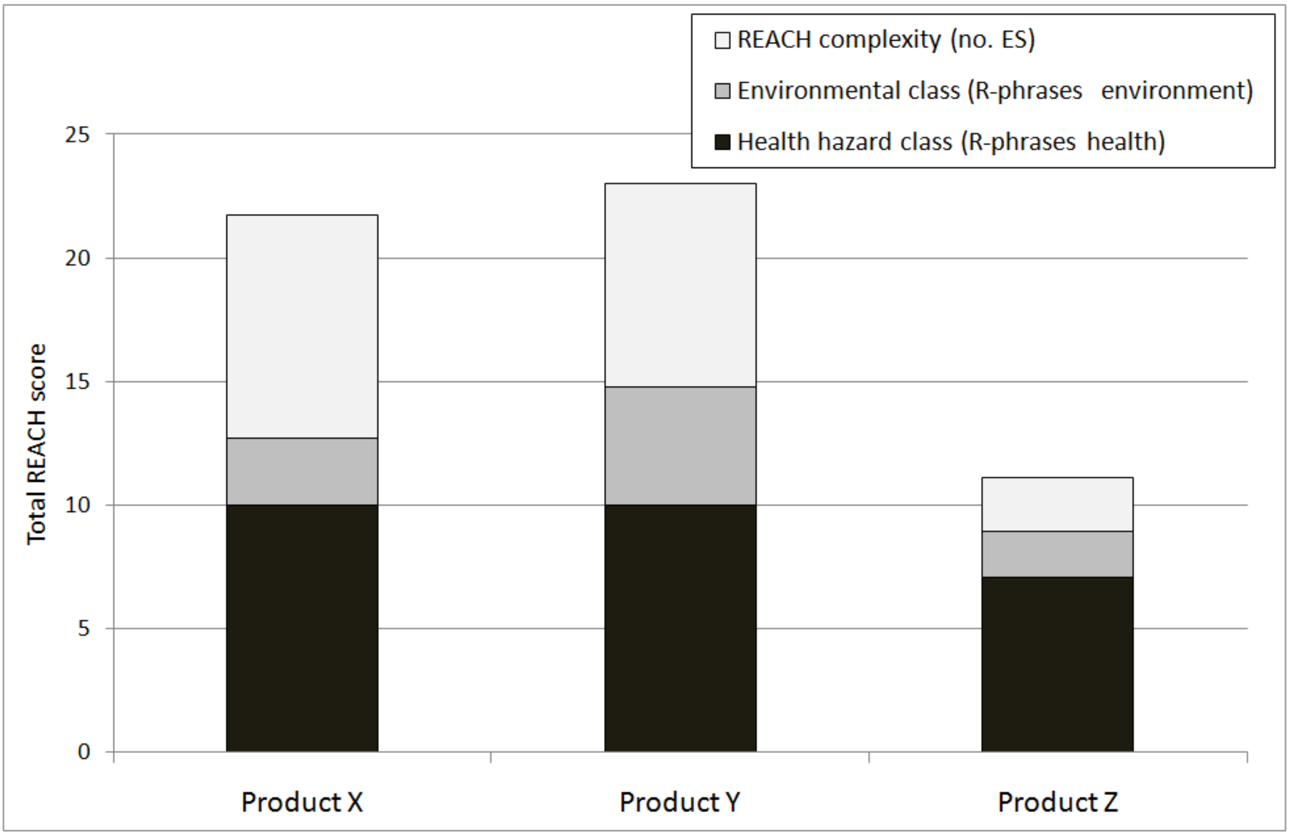

Fig. 4 *REACH Complexity, environmental hazard and health hazard for Two-Component Coatings Products X, Y and Z.*

4 Discussion

The methodological basis for the strategy tool presented in this paper is in a similar form to the Eco-portfolio matrix presented by Brezet et al. (1997), and the portfolio strategy matrix (Hedley in De Wit and Meyer, 2004); both of which were inspired by the Boston Consulting Group's general Growth-Share Matrix (Kotler in Brezet et al. 1997). In the Eco-portfolio matrix, the y-axis is a scale of potential environmental merit, while the x-axis represents market potential. The Strategy Tool presented here contains more complex environmental information, with each axis representing product qualities; the y-axis (VOC concentration) is one indicator of environmental quality, while the x-axis represents an indicator incorporating three different REACH aspects. REACH Complexity and health and environmental risk indicators are combined (as described above) to make the index represented along the x-axis, called Total REACH score. Financial information (raw materials costs) was incorporated in the size of the spheres presented in the figures. Thus the Strategy Tool presented here presents a more complex picture than the Eco-portfolio matrix, incorporating several environmental quality indicators into the tool.

The indicators were proposed by Jotun experts and developed through an iterative process. A set of potential indicators were identified, data collected for these and preliminary results obtained. These results were presented and discussed with key personnel in Jotun's Innovation and Environment teams, as well as product development personnel in Jotun's laboratory. Based upon these presentations and discussions, revisions were made and the indicators presented in this paper were the result of this work. One example of an indicator tested that is not included here is REACH Risk, which was defined as the risk that a raw material could become unavailable, owing to the supplier's failure to register the material under REACH. A scale for this was developed (based on responses to a questionnaire Jotun had sent to its suppliers, as well as knowledge about the size, capacity and location of the given supplier), but this indicator was deemed more useful at another stage in Jotun's innovation process, where the assessment of suppliers takes place. The indicators presented in this paper represent product related aspects that are important for the company and cover regulatory requirements imposed by REACH, classification demands for health and environmental hazard and draft VOC demands linked with economic information. The current version of the tool uses R-phrases, but this will be possible to translate into Hazard Phrases (H-phrases) as a result of CLP in the future.

The REACH Complexity, health and environmental indicators used are given equal weight in the strategy model. However, other companies performing this type of strategic analysis may have other priorities and choose to weight these REACH aspects differently. It is entirely possible that producers further up in the supply chain would need to have a greater emphasis on REACH Complexity, particularly as the burden for documentation lies with the producers, or importers of a given product (Commission of the European Communities, 2007). Weighting of parameters concerning human health, occupational health and the environment is a difficult area (Steen 2006, Cortner 2000, Finnveden 1997) and inevitably means introducing bias (Wilholt, 2008). Assigning equal value to each indicator is also giving them equal weight and is in itself a form of valuation. The valuations used in the work presented here have been made through collaboration with experts in the company and reflect the ranking of issues that these experts have deemed most appropriate for the purpose (to include REACH Complexity, health and environmental indicators in their product development process). Further work on the implications and results of these value choices would strengthen the tool.

Olsen et al. (2001) identify areas of more thorough analysis that would be advantageous. Some of the areas identified are a strategy for common use of LCA and risk assessment (RA) in the priority setting of product groups submitted to an LCA. The Strategy Tool information presented in Figures 1 and 2 does this. It can be used strategically to consider a company's product portfolio and identify products with improvement potential. Products that have good VOC and REACH performance can be easily identified and thus targeted for greater marketing efforts. Products that have poor performance (whether REACH score, VOC concentration, or economically) can be identified and compared to the best products; transferring knowledge about good performance and identifying strategic improvement options for the other products. The most drastic of these options may be that the company decides to remove a given product from their portfolio entirely.

VOC concentration has been chosen as an important indicator for these specific products for Jotun. The tool can be readily adapted to environmental indicators that are relevant for other companies and other product groups. The work presented here assumes that product experts in the company know the most pressing environmental issues for their product group. This also relies on the authorities choosing the appropriate focus for this industry. There are several examples in modern history where product development has been driven by a specific driver, or indicator and led to unexpected consequences. Well known examples are the unexpected effects of pesticides and biocides in focus in the 1960s (Carson 1962) and brominated flame retardants. These flame retardants are in wide use in society today, in electronics, furniture and other applications. They are useful chemicals, helping to inhibit the spread of fire, and are thus meant to save lives. However, in the long term they have been seen to build up in human body fat and in the body fat of other mammals. They are persistent, bioaccumulative and toxic, thus they have long term effects on the health and ability of organisms to reproduce, affecting biodiversity (Macgregor et al. 2010, Brown et al. 2006, Norén and Meironyté 2000). Such unintended consequences might have been avoided had multiple drivers been taken into account during product development; the Strategy Tool provides product developers valuable information towards avoiding such a scenario. The authors do not claim that this tool eliminates this problem, but the presentation of several indicators at once enhances the ability of product developers to understand complex trade-offs between different health and environmental aspects in the product development process.

The strategy tool presented in this paper has been described internally in Jotun as showing the “environmental/health footprint" of new (and existing) products. The environmental performance of new, or existing products can be compared to a reference product (whether that be best in class, new, or old products). It has already been used in Jotun to generally raise consciousness about these aspects and include them in the product development process. Their product development process is structured with specific “Decision Gates” (or milestones) where the information available from this Strategy Tool will be used. The tool has also been identified as particularly useful in development work and selection of raw materials where environmental and/or health aspects are important drivers. The results obtained from preliminary use of the tool have also given the product development team a visualisation of several environmental issues at once, which has led to changes in thinking in some areas. An example of this is the drive to reduce VOC content to the lowest possible level. The strategy tool has enabled them to see that this reduction comes at a price, with some common solutions to the VOC problem leading to an increase in hazard levels (for example a higher content of low molecular weight epoxy, Tavakoli 2003). Thus continuing to develop products with a good margin under the VOC limit can be more important than a coating solution without VOC content.

The team at Jotun has identified that it is a resource intensive exercise to register test raw materials in the strategy tool and will not recommend this in all projects. However, the company sees specific product applications where it can be used to support documentation and communication of environmental/health specifications. Benefits are foreseen in generally supporting learning about existing and new technologies, as well as communication of environmental and health aspects internally. It is possible that the information may also be used for external communication in the future, but its current status is as an internal tool.

Several limitations came to light throughout the process of developing and using the Strategy Tool. Whole paint systems (consisting of several multi-component products) are too complicated for the current version of the tool; although it would be relatively simple to adapt it to include the levels of additional information that would be needed for a multi-layer two-component product system (as is the case for coatings products applied to offshore installations today). Additional performance requirements such as application properties, durability and corrosion protection are also important in the product development process and are not currently included. Inclusion of these product qualities could be explored in future development work. The x-axis in Figures 1 and 2 represents an aggregated indicator, incorporating several REACH factors; perhaps the y-axis could also represent an aggregated product quality indicator in the future.

The cost dimension of the tool could be improved. The present use of raw material costs does not adequately reflect the economical drivers for Jotun in the development of a new product. The indicator is a reasonable screening approach to compare products, but expected margins and potential market price analysis would add value to this information. This is however not possible when the tool is being used in an R&D process to assess new products that have not yet been released onto the market.

The tool in its current form communicates information about meeting requirements in REACH legislation, classification and labelling legislation and VOC requirements. It will also enable Jotun to show development beyond legislative requirements. Further consideration should be given to whether it is important to incorporate other legislative requirements in Jotun's version of the tool in the future. The Strategy Tool gives a framework and an infrastructure that can be adapted to consider product development issues in the light of pertinent legislative requirements for any other groups of products. Further work, testing the tool with products produced by the other industrial partner in the Innochem project, HÅG, will contribute to verifying this.

Training is important for employees using the tool. It is important to select comparable products and enter the data correctly. Interpretation of the figures also requires some training. For example, if one product scores 10 on a given scale, how much better is that than scoring 12? Including limit values on the figures (such as the one for VOC in Figure 2) aids the reader in their interpretation. Interpretation of the information presented is a challenge to those who have not used the Strategy Tool previously. However, those key personnel involved in the development of the tool can act as expert users in their teams and spread the knowledge about the data input required and the interpretation of the results. Learning by doing will be an important way of implementing the tool actively in Jotun's organisation and increasing the know-how about the tool (Ryle 1949, Lundvall and Johnson 1994, Levin and Klev 2002). The tool will be included at the relevant Decision Gate in the Jotun innovation process.

Some important limitations were identified in the development process for the Strategy Tool. As mentioned above, coatings are products where durability is important, which is an aspect not addressed in the tool in its current form. The tool has two ways in which it considers environmental aspects; environmental risk phrases and VOC concentration. Carbon footprint, the life cycle perspective (including durability in the form of functional lifetime, Lagerstedt et al. 2003, Hanssen 1997) and potentially positive environmental contributions resulting from using the product are not covered in the current Strategy Tool. Further case study work using different environmental indicators for a range of products will be performed in the Innochem project, in order to explore how choosing different environmental indicators can affect product development and company strategy. HÅG (now part of Scandinavian Business Seating) produces very different products to Jotun (seating solutions, as opposed to coatings). HÅG has previously commissioned life cycle assessments (LCA) for several of their products. Thus there is extensive LCA-based environmental information available for these seating solutions (The Norwegian EPD Foundation, 2011), which will enable further examination of the ramifications of using different environmental indicators in the Strategy Tool.

5 Conclusions

This paper demonstrates a methodology and approach for making tangible improvements in strategy and product development processes through close work with company experts. We have shown how the Strategy Tool can be (and is being) used practically, as an integrated part of company development and innovation processes, streamlining decision-making and hence having a direct influence on the company bottom line. A framework has been developed for analyzing multiple product development drivers simultaneously, in light of specific legislative and/or environmental requirements. The framework can be adapted for a variety of products and for companies working in quite different fields, in response to differing requirements.

Combining health, environment and financial data, with different levels of detail, enables the company to screen potential new product solutions and benchmark these against others in their portfolio. This screening process can identify hot spots and strengths and weaknesses at a relatively early stage in product development. This will enable the company to intensify their efforts on the best products, minimising wasted resources on product development of products that do not meet the standards required for these issues that the company has identified as strategically important for the particular products being developed.

Presentation of several indicators at once enhances the ability of product developers to understand complex trade-offs between different health and environmental aspects in the product development process. Integrating the strategy tool into the existing innovation processes in the company is important in order to maximise the efficiency of use of the information produced and minimise the additional work required by the teams involved.

Acknowledgements

The authors gratefully acknowledge the important contributions made by the companies participating in the Innochem project: Jotun AS and HÅG as, which have made this work possible, as well as the financial support provided by the Norwegian Research Council through the BIA program and the Confederation of Norwegian Enterprises through the workplace environment fund. Thanks also to colleagues in Ostfold Research and Jotun that have been important discussion partners during this work.

References

Brown, F.R., Winkler, J., Visita, P., Dhaliwal, J., Petreas, M., 2006. Levels of PBDEs, PCDDs, PCDFs, and coplanar PCBs in edible fish from California coastal waters. Chemosphere 64 (2) (Brominated Flame Retardants (BFRs) in the Environment), 276-286.

Brezet, H., van Hemel, C., (Ed.s), 1997. Ecodesign. A Promising Approach to Sustainable Production and Consumption, first ed. United Nations Environment Programme, France.

Carson, R., 1962. Silent Spring. Penguin Classics reprint 2000.

Cefic and DUCC, 2009. REACH: Exposure scenarios for preparations. Methodology for the identification of substances that represent the dominant risks to human health and/or the environment and the drivers for risk management measures. The European Chemical Industry Council (Cefic).

Commission of the European Communities, 2007. Regulation (EC) No 1907/2006 of the European Parliament and of the council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC and 2000/21/EC. Off. J. Eur. Union L 136 of 29.5.2007. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:136:0003:0280:EN:PDF

Commission of the European Communities, 2008. Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (1).
Off. J. Eur. Union L 353, Volume 51, 31 December 2008.P 1-1355.
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:353:0001:1355:EN:PDF

Courtner, H.J., 2000. Making science relevant to environmental policy. Environ. Sci. & Policy 3, 21-30.

Council Directive 67/548/EEC of 27 June 1967 on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous components. Off. J. Eur. Union L, 16.08.1967, 0001 – 0098.

Directive 1999/45/EC of the European Parliament and of the Council of 31 May 1999 concerning the approximation of the laws, regulations and administrative provisions of the Member States relating to the classification, packaging and labelling of dangerous preparations. Off. J. Eur. Union L 200 , 30.07.1999, 0001 – 0068.

De Wit, B., Meyer, R., 2004. Strategy: Process, Content, Context, third ed. Thomson, London.

The European Parliament and The Council Of The European Union, 2004. Directive 2004/42/CE of the European Parliament and of the Council of 21 April 2004 on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain paints and varnishes and vehicle refinishing products and amending Directive 1999/13/EC. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32004L0042:EN:NOT Accessed 4 January 2011.

HSE, 1999. COSHH essentials. Easy steps to control chemicals. Control of substances hazardous to health regulations. HSG193. HSE books, Surrey, UK.

ECHA, 2008a. Guidance on information requirements and chemical safety assessment. Part D: Exposure Scenario Building, version 1.1 http://guidance.echa.europa.eu/docs/guidance_document/information_requirements_part_d_en.pdf Accessed 27 December 2010.

ECHA, 2008b. Guidance on information requirements and chemical safety assessment. Part E: Risk Characterisation. http://guidance.echa.europa.eu/docs/guidance_document/information_requirements_part_e_en.pdf?vers=20_08_08. Accessed 27 December 2010.

ECHA, 2010. http://guidance.echa.europa.eu/about_reach_en.htm. Accessed 25 March 2010.

Finnveden, G., 1997. Valuation Methods Within LCA – Where are the Values? Int. J. Life Cycle Assess. 2(3), 163-169.

Hanssen, O.J., 1997. Sustainable Industrial Product Systems. Integration of Life Cycle Assessment in Product Development and Optimization of Product Systems (PhD Thesis). Faculty of Machine Engineering and Material Sciences, The Norwegian University of Technology and Sciences, Trondheim.

Hanssen, O.J., Asbjørsen, O.A. 1996. Life Cycle Optimization Model for Environmental Performance of Product Systems (CYCLOPS), unpublished manuscript in Hanssen OJ (1997) Sustainable Industrial Product Systems (PhD Thesis). Integration of Life Cycle Assessment in Product Development and Optimization of Product Systems. Faculty of Machine Engineering and Material Sciences, The Norwegian University of Technology and Sciences, Trondheim.

Klev, R., Levin, M., 2009. Forandring som praksis: Læring og utvikling i organisasjoner (”Learning and development in organisations”). Fagbokforlag, Bergen, Norway.

Lagerstedt, J., Luttropp, C., Lindfors, L.G., 2003. Functional Priorities in LCA and Design for Environment. Int. J. Life Cycle Assess. 8(3), 160-166.

Lundvall, B., Johnson, B., 1994. The learning economy. Industry and Innovation 1(2), 23-42.

van Leeuwen, C.J., Vermeire, T.G., (Eds.) 2007. Risk Assessment of Chemicals: An Introduction. Springer, The Netherlands, pp 511-551.

Macgregor, K., Oliver, I.W., Harris, L., Ridgway, I.M., 2010. Persistent organic pollutants (PCB, DDT, HCH, HCB & BDE) in eels (Anguilla anguilla) in Scotland: Current levels and temporal trends. Environ. Pollution 158(7), 2402-2411.

Norén, K., Meironyté, D., 2000. Certain organochlorine and organobromine contaminants in Swedish human milk in perspective of past 20–30 years. Chemosphere 40, 1111–1123.

Ryle, G., 1949. The concept of mind. Barnes, New York.

Steen, B.A., 2006. Describing Values in Relation to Choices in LCA, Int. J. Life Cycle Assess. 11(4), 277-283.

Tavakoli, S.M., 2003. An assessment of skin sensitisation by the use of epoxy resin in the construction industry. Research Report 079. Health and Safety Executive, Her Majesty's Stationery Office, Norwich, UK.

The Norwegian EPD Foundation, 2011. EPD-registry furniture. http://www.epd-norge.no/category.php?categoryID=435. Accessed 27 March 2011.

Wilholt, T., 2008. Bias and values in scientific research. Studies in History and Philosophy of Science 40, 92-101.

UN GHS, 2005. Globally Harmonized System of Classification and Labelling of Chemicals (GHS). http://www.unece.org/trans/danger/publi/ghs/ghs_rev01/01files_e.html. Accessed 1 April 2011.

Ökopol, 2009. European Commission Service Contract N°070307/2007/483710/Mar/C3 Implementation And Review Of Directive 2004/42/Ec
(European Directive Limiting The Voc Content In Certain Products – Current Scope: Decorative Paints And Varnishes, Vehicle Refinishing Products) Final Report (2 Parts) Part 1: Main Report, Annexes 1-25 10 November 2009
http://ec.europa.eu/environment/air/pollutants/pdf/paints_report.pdf

Combining Chemical Risk Phrase Information with a Life Cycle Assessment Approach for Product Development

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Abstract

Purpose

This paper presents a prototype model for linking chemical risk information with a life cycle assessment (LCA) approach to product development (the REACH/LCA Screening Tree Tool), in answer to the research question: *Is it possible to combine REACH hazardous risk information with LCA methodology in product development?* The paper also presents results from combining use of the tool on an individual product level and a coatings solution level (i.e. the two-component solution the customer would apply) in order to work towards answering the research question: *Will the life cycle approach result in different priorities for product development than a purely hazardous risk information approach?*

Methods

SimaPro 7.3.0 was used to develop a tool to combine LCA with Risk Phrase information for health and environmental hazards encompassed by REACH and the CLP Directive. Real product development cases are used based on Ostfold Research's collaboration with industry - specifically a coatings company.

Results

Some results from testing the prototype tool are presented and its application in product development within the coatings company and for other companies is discussed.

Conclusions

The work presented in this paper enables the first research question to be answered in the affirmative. The second research question has only been partly answered, but the work indicates the likely answer is also affirmative.

The Screening Tree Tool links with a product development strategy tool previously presented by the authors. This combination of tools enables a company to efficiently identify which products to consider in more detail and then provide detailed information about where the hot-spots arise for that product, which raw materials contribute the most to these and which chemicals in these raw materials are the most significant.

Keywords: REACH, Product development, Risk phrases, Hazard, Paints, Coatings.

1 Introduction

This paper presents work performed in close collaboration with Jotun, as part of the Innochem project (Hanssen 2010). Innochem is a collaborative project involving companies (Jotun and HÅG) and research institutions (Ostfold Research, NIVA, UiO and Aalborg University) financed by the Norwegian Research Council (BIA program, Brenna 2010) and participating companies. The specific research presented here shows how chemical hazard classification data, presented in the form of risk phrases, has been combined with a life cycle assessment approach in order to give input to the product development process in Jotun. The tool developed for this work is described and presented along with examples of the results that were obtained. The applicability of these results for product development purposes is described and discussed.

Jotun uses IHS's Intelligent Authoring™ program (Atrion 2011) for classification of paint products in order to identify the classification and labelling requirements. In Europe, this gives the risk phrases (R-phrases) needed for hazard labelling of products based on chemical content on a mass basis. The information coming from the Intelligent Authoring programme is not in visual form, or suitable to combine with an LCA approach. Visualisation of this information and combination with the LCA approach will be addressed in this paper.

Giudice et al. (2006) provide a good overview of the types of tools and approaches available for a life cycle approach to product design. However, tools dealing with toxicity and chemical hazard are not specifically adressed. Minimisation of polluting, toxic, or environmentally dangerous materials is part of the guidelines for life cycle design given. Giudice et al. (2006) also describe issues of strategic importance in addition to the life cycle approach. Human health and environmental hazards, represented by risk phrase labelling, are examples of what can be included in the multi-criteria approaches they describe. Design solutions are developed to combine a variety of diverse criteria (conventional performance, quality and cost, as well as environmental); the environmental criteria differing according to the type of environmental effect to which they apply.

Finksel (2009) describes both LCA and Risk Analysis as analysis methods that can be used for design decisions. Finksel states that risk analysis information can be factored into a risk/cost/benefit analysis such that the associated trade-offs can be expressly communicated to a variety of interested parties. LCA is also described as a tool that can provide comparisons of design options in terms of their potential adverse effects on humans and the environment; whereas actual risks require more detailed environmental risk assessment methods (risk analysis). However, Finksel does not present any operational link between these tools.

Mattila et al. (2011) test the results from life cycle impact assessment methods for toxicity against expert judgement on chemical risk assessment. This is performed for a nation (Finland), in order to identify priority products at a political level. This is a different level of decision-making, but a current example of an attempt to compare the results from risk assessment with results from toxicity impact assessment in LCA. Mattila et al. (2011) state that the two approaches cannot be directly compared, but should be seen as complementary. Olsen et al. (2001) describe LCA and risk assessment (RA) as two different tools in environmental management, identifying the harmonies, discrepancies and relations between the two tools. They conclude that the conceptual background and purposes of the tools are different, but that there are overlaps where they may benefit from and complement each other. Olsen et al. (2001) identify areas of more thorough analysis that would be advantageous. Some of the areas identified are: a strategy for common use of LCA and

RA in the priority setting of product groups submitted to an LCA, integrations of methodological development regarding assessment of the use phase and further investigation of which data (substance data, emission data etc.) are interchangable between the two tools, and how this can be done. Askham et al. (2011) and the current paper, using the Screening Tree Tool are examples of work that explore some of these issues for further development identified by Olsen et al. (2001).

Saling et al. (2002) and Landsiedel and Saling (2002) describe how human health impacts are important for LCA-based sustainability tools and show how BASF has used human health impacts based on expert valuation of legal classification for relevant substances. Their methodology incorporates the weighting of substance classification and applies it to a product life cycle perspective. Saling et al. (2002) use R-phrases and hazard symbols as the basis for their logarithmic scoring system (values of 1, 10, 100 or 1000 assigned depending on the level of hazard) and state that in future the assessment base can be “formed directly from R-phrases, which can be linked to assessment numbers”. The Screening Tree Tool described in this paper presents an operational approach to this problem in a current software tool (PRé Consultants 2011), incorporating R-phrases and threshold limit values for classification of both human health and environmental hazards. This approach incorporates new developments arising from REACH (Commission of the European Communities 2007) and Classification, Labelling and Packaging directives (CLP regulation, Commission of the European Communities 2008). Saling et al. 2005 describe further work in BASF that incorporates ecotoxicity into their LCA-based sustainability tool for comparative product assessment. Similarities and differences between the BASF approach and the Screening Tree Tool are discussed below.

Pant et al. (2004) compare results from LCA with results from an environmental risk assessment (ERA) for three detergent products. They use this case study as the basis to discuss similarities and differences between the toxicological characterisation of chemicals in life cycle impact assessment (LCIA) and (environmental) risk assessment. They encounter problems in data availability, particularly for physico-chemical parameters and chronic aquatic ecotoxicity. The need to link to ongoing REACH efforts, in the context of the chemical regulations on an EC level, is also identified. The work presented in this paper provides an operational link, bridging ERA/RA and LCA, and uses information that will be readily available as a result of REACH and CLP information.

The work presented in this paper describes the structure and results from a tool developed by the authors using SimaPro software (PRé Consultants 2011); this Screening Tree Tool is not an existing tool within the SimaPro software.

2 REACH

The Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) directive was adopted by the European Union (EU) in December 2006, and requires companies importing or producing substances (>1 tonne/year) in the EU and EEA regions to register these substances with the EU’s Chemicals Agency (ECHA). The requirements of REACH are relevant both for individual substances and substances in mixtures (e.g. paint), although the registration demand is for substances only. REACH requires companies to register the substance’s identity, classification and labelling, test results and propose further tests for the substance, exposure potential to humans and different environmental compartments and recommendations for safe use. The requirements for REACH increase with the quantities of substances imported / produced, and with the hazard levels. If a company operates with quantities greater than 10 tonnes/year, a Chemical Safety Report (CSR, risk assessment) is required for the substance. If a chemicals company does not comply with REACH, it cannot sell its products in the European market (Commission of the European Communities 2007).

REACH entered into force on 1st June 2007 and is meant to streamline and improve the EU's former legislative framework on chemicals. REACH places the responsibility on industry to carry out chemical safety assessments and manage the risks that chemicals may pose to health and the environment. The aims of REACH are (ECHA 2010, van Leeuwen and Vermeire 2007): to improve the protection of human health and the environment from the risks that can be posed by chemicals; to enhance the competitiveness of the EU chemicals industry; to promote alternative methods for the assessment of hazards of substances; and to ensure the free circulation of substances on the internal market of the EU.

At the present time REACH requires that health and environmental risks associated with chemicals are expressed as risk phrases (R-phrases) in line with international hazard labelling standards (ECHA 2008) and European hazard labelling directives (Council Directive 67/548/EEC, Directive 1999/45/EC). It should be noted that R-phrases will be replaced by a new system defined in the CLP regulation, which has been adopted for pure substances on 1st December 2010 and will be adopted for products by 1st December 2015 (CLP regulation, Commission of the European Communities 2008). CLP uses hazard phrases (H-phrases), rather than R-phrases, introducing the new EU system for classifying and labelling chemicals, based on the United Nations' Globally Harmonised System (UN GHS 2005). Annex VI (Table 3.1, Commission of the European Communities 2008) gives harmonised classification and labelling lists, whereas Annex VII (Table 1.1, Commission of the European Communities 2008) provides a translation from the R-phrases given in directives 67/548 and 1999/45 to the new CLP H-phrases. Thus, it will be necessary to translate the R-phrase information incorporated in the tool into H-phrases in the future, but for Jotun's current purposes, R-phrases were most relevant.

ECHA (2009) describes the links between CLP and REACH as follows: "Many provisions of CLP are closely linked to provisions under Regulation 1907/2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) ..." REACH links are also noted in text boxes in relevant sections throughout the guidance (ECHA 2009). These links mean that hazard labels required for CLP are also considered a link to REACH. The responsibility to assess risks and hazards of substances is given to industry in the REACH regulation ("the natural or legal persons that manufacture or import substances", Commission of the European Communities 2007); risk and hazard information forms the scientific basis for labelling to be included in safety data sheets for substances and mixtures; both are again linked to CLP and to REACH.

3 The REACH/LCA Screening Tree Tool

The REACH/LCA Screening Tree Tool was developed in close collaboration with Jotun, in order to ensure relevance to and usefulness in their product development process. The tool was developed using the SimaPro 7.2 software (PRé Consultants 2011). This section of the paper contains a description of how the tool was constructed in SimaPro.

The Social Issues category of substances in SimaPro was used to enter R-Phrases and points (pt) units were used. Relevant chemicals that are present in the raw materials aquired by Jotun were entered as “Inputs from nature”. This is not in accord with the principle that inputs from nature are primary flows to and from the earth, as these chemicals are actually components flowing between systems in the technosphere (company to company, rather than nature to technosphere flows). However this construction was needed in order to achieve the structure desired for this screening tool. The relevant R-phrases were entered under “known inputs from technosphere (materials/fuels)” and production data for the substance was also linked here.

R-phrase classification for coatings products was determined by the result of a simple calculation (in line with the classification of other chemical mixtures). An R-phrase was known to apply to a chemical mixture when the Applicability Ratio (1) was greater than or equal to 1, where the Applicability Ratio is defined as the ratio of quantity of substance present (in mass%) to the minimum concentration (in mass%) for that R-phrase to apply.

$$\frac{Quantity\ \ present\ (mass\%)}{Limit\ \ for\ classification\ (mass\%)} \qquad (1)$$

The quantity entered in SimaPro (“known inputs from technosphere”) for a given R-phrase for a given substance was the inverse of the concentration limit. If several R-phrases applied to a given substance, all of these were entered, each with its respective inverse concentration limit. The concentration limits (also referred to in this paper as threshold limit values) were obtained from Atrion (2011), which bases these on legal requirements for substance and product classification and labelling in Europe (Council Directive 67/548/EEC, Directive 1999/45/EC).

$$Hazard\ Indicator = \sum_{i}^{n} \frac{m_i}{C_{Li}} \qquad (2)$$

When the calculations were performed in SimaPro, the mass, m_i, of the substance, i, in the mixture was divided by the limit concentration for the given R-phrase, C_{Li}, in order to obtain the score for the Hazard Indicator, as shown in Equation 2. The amount of the substance present was determined by the product composition, which was entered in the “Product Stages” part of the SimaPro model. A structure was built up using raw materials (sometimes consisting of several substances) in the “Assembly” part of Product Stages. These raw materials were then used in the Life Cycle part of the Product Stages structure in SimaPro. This enabled two component product systems to be constructed in the model using the correct mixing ratios.

In order to facilitate the calculations a new “Method” was needed in the Impact Assessment part of the SimaPro model. This method was split up into characterization of hazard and exposure pathways, as illustrated in Figure 1. Figure 1 is constructed in a similar fashion to the figure illustrating the stepwise aggregation of information in LCA from Baumann and Tillman (2003, p30).

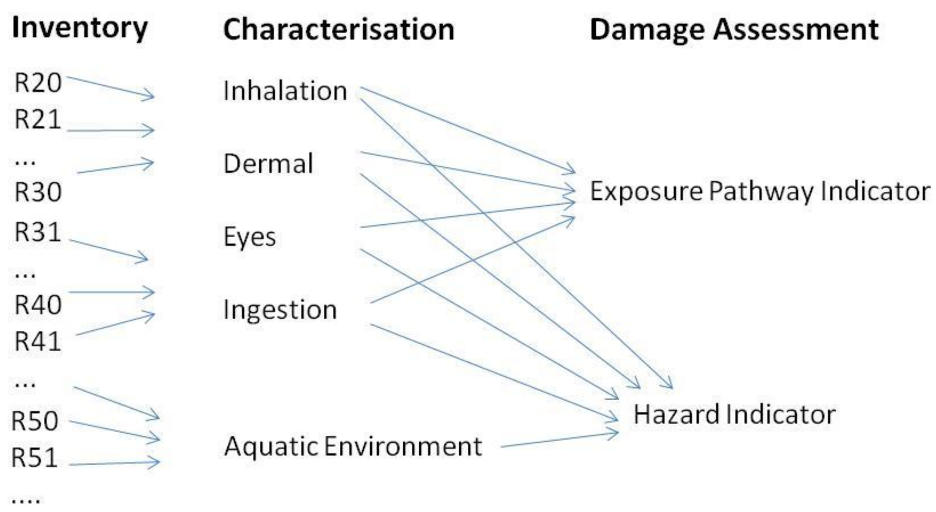

***Fig. 1** The structure of the method devised for calculation of Hazard Indicator and Exposure Pathway Indicator.*

The Hazard Indicator was calculated in points, by assigning 1 point per risk phrase point for all of the risk phrases entered into the method. The impact assessment part of the method, entitled "Hazard Indicator" does not weight this information further, but summarises it. The Hazard Indicator enables the user to identify the most important risk phrases and their contribution to the labelling requirements for the given product.

The exposure pathway part of the method is such that the human exposure pathways Inhalation, Dermal, Eyes and Ingestion are each separate impact categories under "Characterization" in the method. This impact pathway information in the Characterization part of the SimaPro Method is used in the Damage Assessment part of the method as the basis for the "Exposure Pathway Indicator" (see Figure 1 and Equations 3 and 4), which only incorporates human health risk phrases.

$$Exposure\ Pathway\ Indicator\ (EPI_{humanhealth}) = EPI_{inh} + EPI_{D} + EPI_{E} + EPI_{Ing} \quad (3)$$

$$EPI_{humanhealth} = \sum_{i}^{n}(R_{NInhi}\frac{m_i}{C_{Li}} + R_{NDi}\frac{m_i}{C_{Li}} + R_{NEi}\frac{m_i}{C_{Li}} + R_{NIng_i}\frac{m_i}{C_{Li}}) \quad (4)$$

The subscripts *inh*, *D*, *E* and *ing* denote the exposure pathways inhalation, dermal, eyes and ingestion respectively. R_N is the R-phrase with number *N*.

The practical outcome of the analysis presented here is different for the two different indicators. The Hazard Indicator provides the user with information about the need for hazard labelling for a given product (mixture of substances). If the amount of a substance present in the product is greater than the concentration limit for labelling (i.e. the Applicability Ratio is greater than, or equal to 1), then labelling the product with a given risk phrase is required. The Exposure Pathway Indicator provides information about which human health exposure pathways are most important for the product, which in turn indicates which risk management measures (for example protective equipment, such as gloves, masks, or ventilation systems) should be recommended for a given product.

4 Results

Results for the different products were obtained using the Calculation Setups part of SimaPro. The products used as cases are under development as part of Jotun's offshore coatings range. Each of the individual products (six cases) are in practice used as components in two-component mixtures ("Coating 1" is a mixture consisting of Products A and B), which are blended on site, immediately prior to application. The model structure used enabled the SimaPro user to obtain results for each of the six component products, or for the product mixtures to be applied to the construction. Figure 2 shows the type of results that can be obtained for the Aquatic Environment pathway (characterisation level result, as illustrated in Figure 1); Figure 3 shows the results for Hazard Indicator ("Damage Assessment" level result, as illustrated in Figure 1). Both of these figures are results for a single product (Product A), while Figures 4 and 5 show the same indicators for the two-component product system (Products A and B mixed in a 4:1 ratio). The product tree figures that are presented in Figures 2-5 were all created in SimaPro using a 1% cut-off level, thus only showing elements that contribute more than 1% of the total score for the indicator. This cut-off level was chosen in order to simplify the figures presented. Also, such R-phrases, with an Applicability Ratio much lower than one, have no influence on product labelling.

Note that for Figures 2-5the names and quantities of chemicals have been obscured because of confidentiality requirements. The abbreviation RM is for raw material and C is for chemical ("substance" in REACH terminology). The numbering of raw materials and chemicals is consistent for all of the figures, thus C 1 in Figure 2 is the same chemical as C1 in Figures 3-5.

In order to explain the information shown in the Screening Tree Tool figures, Figure 2 is used as an example. The value given in the lower left hand corner of the "Product A" box is the "Characterization" level result for the Aquatic Environment (EPI_{aq}, where Hazard Indicator = $EPI_{human\ health} + EPI_{aq}$). Chemical 1 has a Hazard Indicator for the aquatic environment pathway that is shown by the value in the lower left hand corner of the C1 box. This is the sum of the Applicability ratios for the three relevant R-phrases for C1. Classification of C1 with R-phrases R53, R52/53 and R51/53 mean that these R-phrases are shown as connected to C1 by lines. The thickness of the lines represents the Applicability Ratio for the R-phrase for the given chemical, thus Figure 2 shows that R52/53 is more important for the EPI_{aq} than R53.

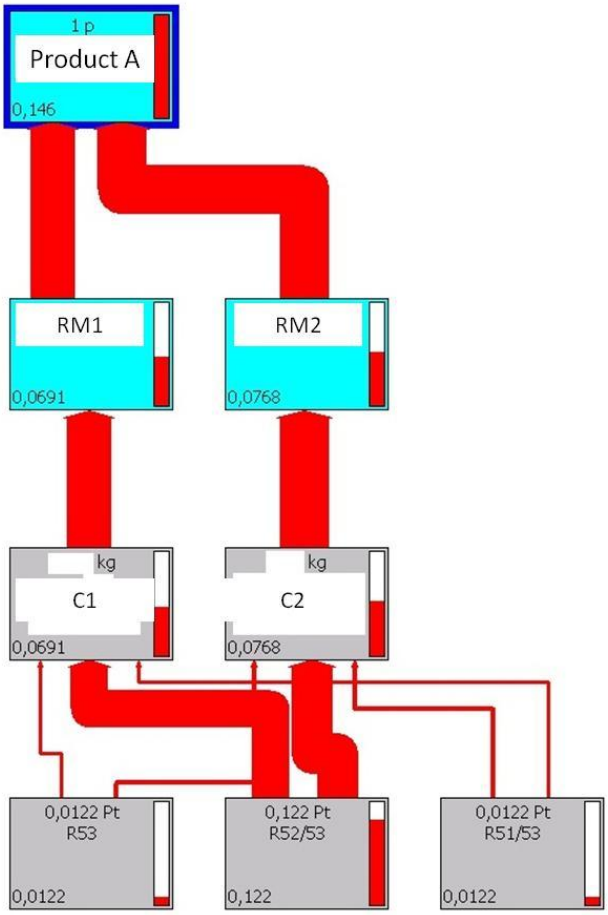

Fig. 2 *The Aquatic Environment Exposure Pathway results for Product A.*

In Figure 2 we see that that none of the chemicals that have a labelling requirement for risk to aquatic environment are present in sufficient concentrations to merit labelling for this risk (the sum of the values for the Applicability Ratio for R53, R52/53 and R51/53 is less than 1, as shown in the bottom left of the Product A box in the figure). Product A contains two raw materials (1 and 2) containing two specific chemicals (1 and 2) that contribute more significantly than any others to the potential risk to aquatic organisms if they were exposed to the aquatic environment.

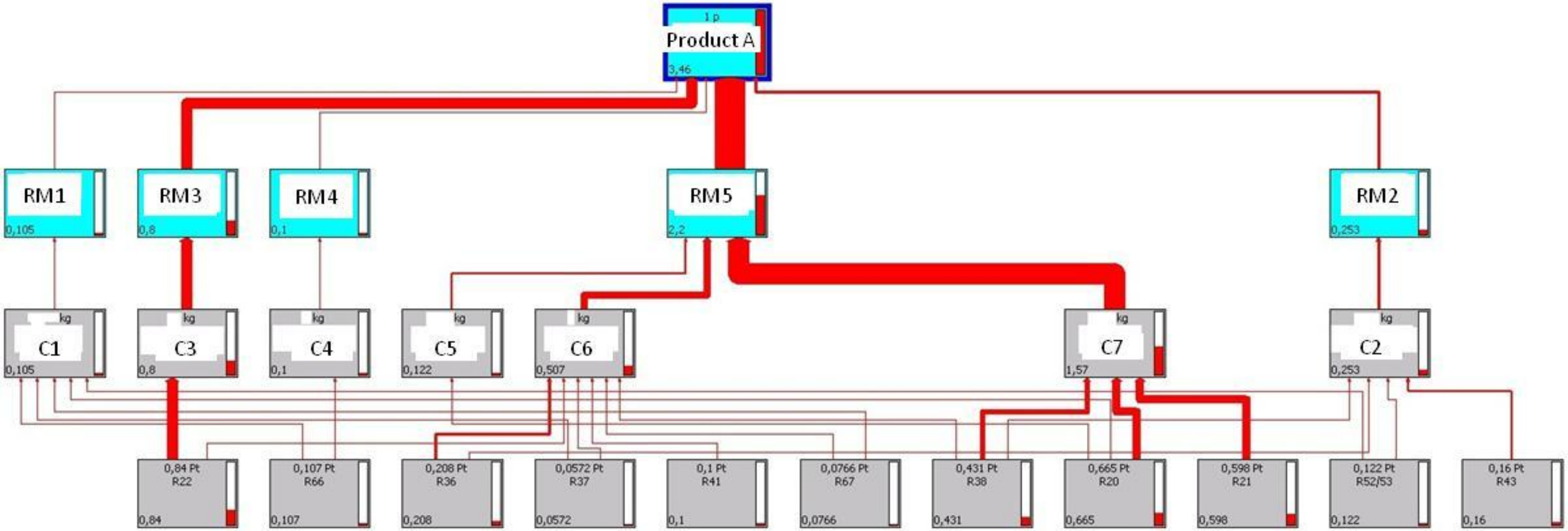

Fig. 3 *Hazard Level Indicator results for Product A.*

Figure 3 shows the Hazard Level Indicator results for Product A. This gives an overview of all of the relevant risk phrases that could apply to Product A. The figure gives us the immediate impression that there are 2-3 chemicals that are the most important for this product (C3, C6 and C7) and these are found in two of the raw materials (RM3 and RM5). Figure 3 shows that the results for The Applicability Ratio for all of the relevant R-phrases are below 1 (i.e. the numbers shown in the bottom left of the R-phrase boxes in the figure), so this would normally imply no R-phrase labelling required for Product A. However, R-phrases 20-22 are additive (Directive 1999/45/EC) and thus when adding the values presented for R20-22 for Product A in Figure 3, the sum is approximately 2.1, which means that Product A must be labelled with R-phrases R20, R21 and R22.

Coating 1 is a product that consists of Product A and Product B combined in a 4:1 ratio. Figures 4 and 5 show results for the same Damage Assessment indicators as for Product A in Figures 2 and 3. Figure 4 gives the user a clear picture that the potential risk to the aquatic environment is not significant for Coating 1 (the sum of the Applicability Ratios for the relevant R-phrases is less than 1). Chemical C8 has the largest contribution to the aquatic environment results than any other chemical, owing to the C8 content being closer to its labelling limit than the other chemicals in this coating product.

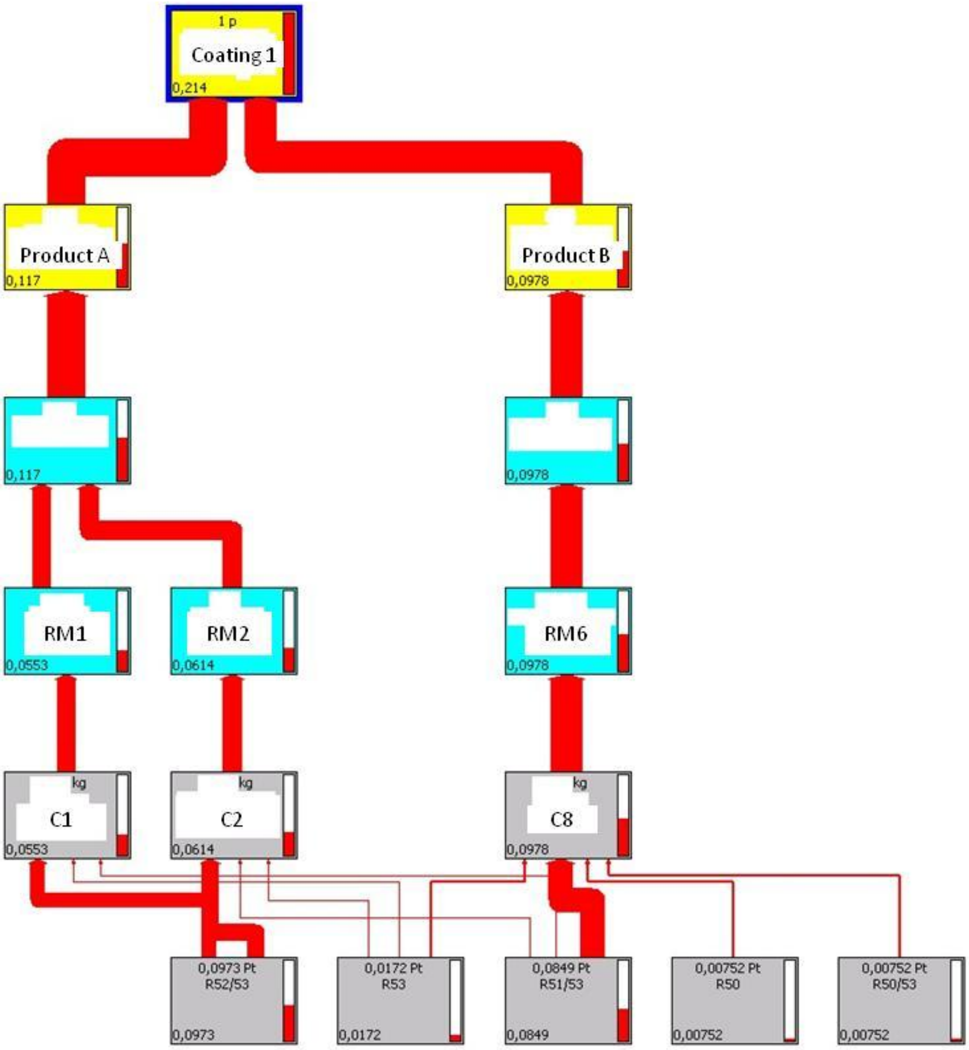

***Fig. 4** The Aquatic Environment exposure pathway results for Coating 1 (Products A and B combined in a 4:1 ratio).*

The Hazard Level Indicator for Coating 1 is shown in Figure 5. The contributions to the risks that can be associated with this coating product come mainly from Product B, but also from Product A. RM7, RM5 and RM3 are shown to be the most significant raw materials. Raw material RM7 is the most significant for this coating product, and C9 is the chemical that exceeds the R43 labelling limit. R20-22 are additive (as described above), and thus the sum of The Applicability Ratio for these R-phrases is of interest. From Figure 5 it can be seen that the sum of the these R-phrases is greater than 1, as a result of the contributions by C3 and C7.

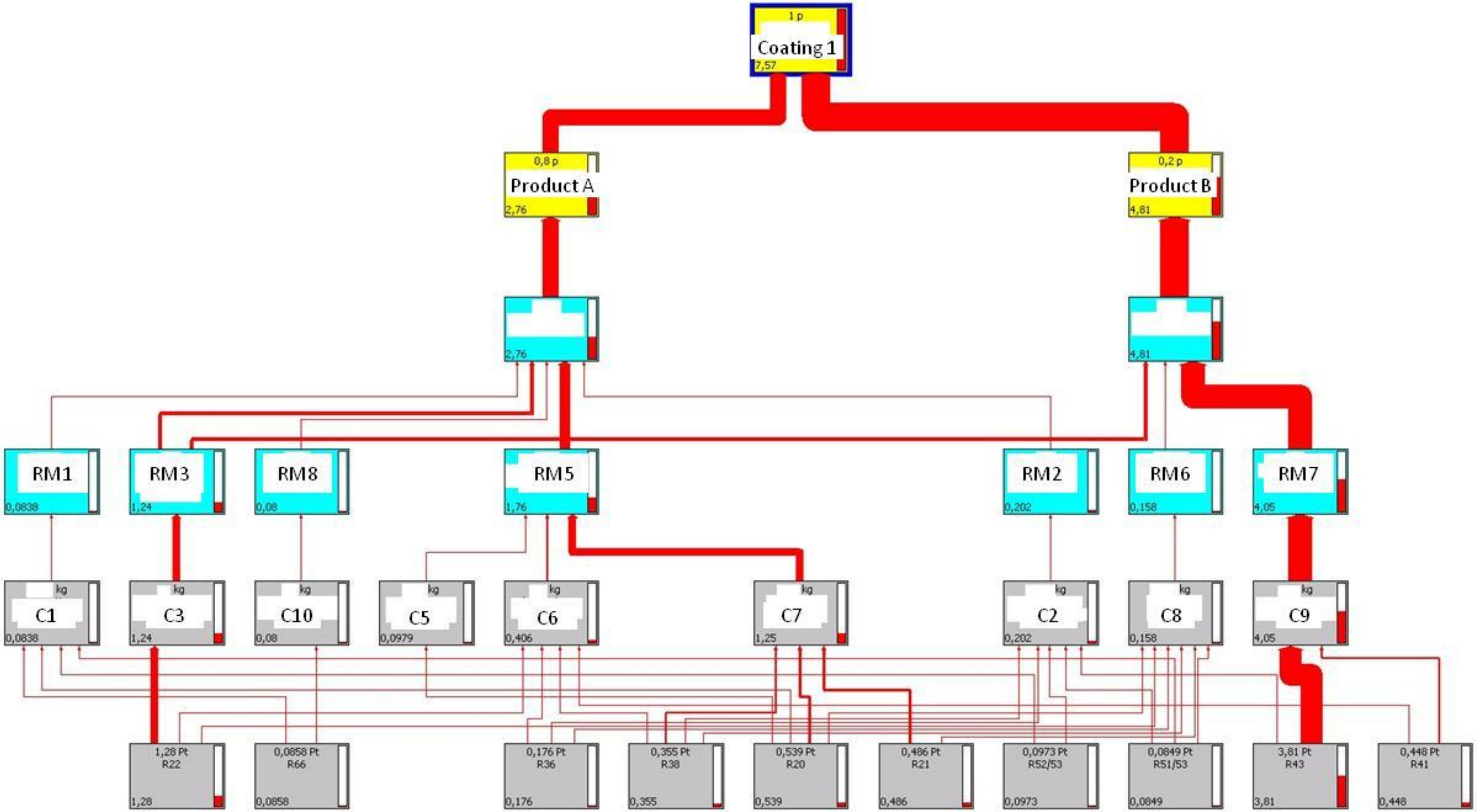

Fig. 5 *Hazard Level Indicator results for Coating 1 (Products A and B combined in a 4:1 ratio).*

5 Discussion

The model structure presented ensures that both the amount of chemical in the product, the hazard of the chemical and the R-phrase determine the hazard level. The weighting of R-phrases depends on the chemical for which the risk phrase applies. Thus the weighting of R-phrases is not performed in the Method part of the SimaPro tool. To do so would be erroneous, since the concentration limit for a given risk phrase is not the same for different chemicals that the same risk phrase applies to. The use of the limit concentration for the given R-phrase for a given chemical is in line with the risk assessment approach used in Mattila et al. (2011). Prioritisation was based on the proximity of observed concentrations to observed environmental quality limits (although their approach is applied to a nation, not a product). The Screening Tree Tool presented here provides information in a visual overview and facilitates the link to an LCA perspective. The R-phrases will be superseded by a new system using H-phrases (Commission of the European Communities 2008), but this can be incorporated into the tool when appropriate for the user (i.e. when the CLP directive is applicable to the company's products).

As described in the Introduction, Olsen et al. (2001) examine the different tools of RA and LCA, identifying harmonies, discrepancies, and relations between the two tools. They identify areas of more thorough analysis that would be advantageous. Two areas that are relevant for the current work are: integrating methodological development regarding assessment of the use phase, and further investigation of which data (substance data, emission data etc.) are interchangable between the two tools. The Screening Tree Tool uses data from classification of chemicals (R-phrase classification and threshold limit values) and begins to combine it with an LCA approach to product development. The work presented in this paper answers the need described in Saling et al. (2002) that in future the assessment base can be "formed directly from R-phrases, which can be linked to assessment numbers". The Screening Tree Tool presents an operational approach to this problem in an existing software framework (PRé Consultants 2011), incorporating R-phrases and threshold limit values for classification. The BASF work also describes incorporating worker exposure and weighting of process steps where human exposure can occur using appropriate expert estimations. Suitable references for this in the future will be Exposure Scenarios, which will be a natural result of REACH (Commission of the European Communities 2007, Askham 2011). BASF have performed further work to incorporate ecotoxicity potential into their LCA-based sustainability tool for comparative product assessment (Saling et al. 2005). In BASF's tool the exposure via the aquatic environment pathway is used; this is another similarity with the Screening Tree Tool, which uses R-phrases for the aquatic environmental exposure pathway. Environmental exposure via other environmental compartments is not included (in either of these tools). Saling et al. (2005) describe their selection of the water compartment for assessing ecotoxicological potential as owing to its relevance and availability of toxicity data. Aquatic toxicity data is relevant for terrestrial and air compartments, because exposure to organisms in soil is often via pore water; as well as air emissions that have more than a very short lifespan also entering the aquatic compartment via rainfall (van Leeuwen and Vermeire 2007). The calculations involved in derivation of the Environmental Score presented in Saling et al. (2005) are clearly related to toxcity data (Environmental Effect Score part of the tool), incorporating a potential environmental impact score, related to distribution and biodegradability factors. The approach presented in this paper (Screening Tree Tool) incorporates physico-chemical properties that indirectly affect distribution and biodegradibility, via the threshold limit values for the given chemicals. Product exposure is not included in the tool presented in this paper, but the potential effects of the exposure and the important exposure pathways are readily available from the Screening Tree Tool in a visual form.

In line with the approaches described in Saling et al. (2002) and Saling et al. (2005), the tool presented here is a simplified approach for comparison of products relative to each other on a scale of potential ecological and human health risk, rather than absolute values.

Bunke et al. (2003) and Bunke and Oldenburg (2005) discuss the ranking of risk phrases and monoethylene glycol (MEG) equivalents as an approach to the need for a hazardous-substance-specific assessment of products and processes. This work is described as similar to Landseil and Saling (2002), as both approaches are based on R-phrases, which are available for many substances and specified in safety data sheets. Bunke and Oldenburg (2005) also conclude that existing indicators for hazardous chemicals can be a valuable tool for product refinement for companies. The Screening Tree Tool presented here is an example of how this can be done in practice.

As described in the “Results” Section of this paper, there are situations where certain R-phrases are additive (for example if the sum of the Applicability Ratio for R20-22 exceeds one). If the user is not familiar with these specific rules for certain R-phrases, they will not immediately see this from the tool in its present form. This means that the wrong conclusions could be drawn about relevant labelling requirements. The Screening Tree Tool is a prototype, and in its current version the authors have not included such specific rules for groups of R-phrases. However, it is clear to the authors that these kind of rules can easily be incorporated by adding levels to the Characterisation, or Impact Assessment part of the tool in SimaPro.

Figures 4 and 5 show the REACH/LCA Screening Tree Tool results for Coating 1. This would not be used as the basis for labelling Coating 1, as this product will never be transported in mixed form. However, it gives product developers at Jotun an insight into the occupation health and environmental hazard aspects of the product application that can be important, with a more functional perspective. A functional perspective for product development is normal in LCA, whereas REACH and the CLP directive (Commission of the European Communities, 2008) are concerned with Product A and Product B level risks and hazards and hazard labelling. Inclusion of this more functional step is part of the work towards combining risk information for chemicals with the LCA approach. The difference in results shown between Figures 2 and 4 and Figures 3 and 5 support the hypothesis that *the life cycle approach can result in different priorities for product development than a purely hazard classification approach*. In order to have a complete life cycle approach, the rest of the product life cycle would have to be included and a functional unit (for example 100m^2 of surface area of an oil rig maintained to a given quality standard over 20 years, Rønning et al. 1995, Axelsson et al. 1999) used as the basis for the assessment. The tool and approach presented in this paper are the first steps needed before further development required to encompass the complete functional unit-based LCA approach.

This Screening Tree Tool links with a product development Strategy Tool previously presented by the authors (Askham et al. 2011). The Strategy Tool is in a similar form to the Eco-portfolio matrix presented by Brezet et al. (1997), but the x-axis in the strategy tool presented in Askham et al. (2011) represents an indicator incorporating three different REACH, health and environmental aspects. The Strategy Tool enables Jotun to obtain graphical representations of groups of products, giving an overview of REACH Complexity, health and environmental indicators (based on R-phrases), VOC levels and financial information. This enables the company to identify products in a given product range that need improvements, while the Screening Tree Tool presented in this paper enables the product development team to obtain a visual overview of where the REACH health and environmental risk issues arise for a given product, or product combination. Combination of these tools enables a company to efficiently identify which products to consider in more detail and provides detailed information about where the hot-spots arise for that product, which raw materials contribute the most to these and which chemicals in these raw materials are the most significant. This information can be used internally, in order to drive product development in a more favourable direction. It can also be used to identify more or less favourable raw materials supplies (and suppliers) for future products. Cases studied in development of the tool included examples where an important chemical for labelling was an unwanted by-product in the raw materials production; this had no functionality but had a significant influence on the labelling requirements for the end-product. This visualization can be used to communicate the importance of such issues to suppliers, perhaps suggesting the level of impurity that would be acceptable (also calculable using this tool).

Fiksel (2009) describes practitioners of life cycle management (LCM) believing that LCM leads to a broader awareness of stakeholder concerns across the supply chain, leading to better business decisions. However he describes standard practice in business decision making as typically confined to financial analysis, even among companies that are recognised as industry leaders in sustainability. The tool developed here is an example of a tool evaluating a product's environmental performance with respect to specific aspects, using defined metrics and indicators (Giudice et al. 2006). The results of the Applicability Ratio, presented in this visual format are not only useful in terms of showing which R-phrase labelling the products would require, but also enabling the product development team to visualise which chemicals are close to the labelling limit value. Jotun has reported the tool's practical value in product development, particularly in cases where there is some flexibility in the product formulation and where chemicals are just above, or just below the labelling limit. The information presented enables product developers in the lab to identify acceptable tolerances in composition for a given formulation. If they are just over a labelling limit, they can see which raw materials and chemicals contribute to this and work actively to reduce the product's R-phrase labelling requirements. This in turn will mean real reductions in potential hazards associated with products. This means that the Screening Tree Tool manages to combine the traditionally "only above threshold" approach for risk assessment with the "less is better" approach that is typical for LCA (Potting et al. 1999).

6 Conclusions

The work presented in this paper enables the authors to answer "yes" to the research question: *Is it possible to combine REACH hazardous risk information with LCA methodology in product development?* The second research question has only been partly answered, as the complete life cycle perspective for coatings was not studied. However, the work presented here gives a clear indication that the chemicals and raw materials identified as the most important for individual products were not necessarily the same for the two-component coating product. This work indicates that it is likely that the answer to the second research question is also affirmative: *Will the life cycle approach result in different priorities for product development than a purely hazardous risk information approach?*

The tool presented in this paper adds value to the authors' previous Strategy Tool work (Askham et al. 2011) by enabling the product development team at Jotun to analyse why particular products achieve a certain REACH health and environmental risk score, then identifying which chemicals are important in specific raw materials from known suppliers. The combination of these screening tools is extremely powerful and aids interdisciplinary collaboration between innovation, product development and environmental management teams in Jotun.

Acknowledgements

The author gratefully acknowledges the important contributions made by the companies participating in the Innochem project: Jotun AS and HÅG as, which have made this work possible, as well as the financial support provided by the Norwegian Research Council through the BIA program and the Confederation of Norwegian Enterprise through the workplace environment fund. Thanks also to Fredrik Ringdal, Marte Rindal Jacobsen and Mark Goedkoop who have made valuable comments during development of the tool; Per Christensen who has made valuable comments to the manuscript, as well as colleagues in Ostfold Research that have been important discussion partners during this work.

References

Askham C, Gade AL, Hanssen OJ (2011) Combining REACH, Environmental and Economic Performance Indicators for Strategic Sustainable Product Development. Submitted to J. Environ Management

Askham C (2011) REACH and LCA – Methodological Approaches and Challenges. Submitted Int J Life Cycle Assess

Atrion (2011) Intelligent Authoring™. http://www.atrionintl.com/en/products-compliance-solutions/on-premise-solutions/intelligent-authoring.html. Accessed 27th May 2011

Axelsson U, Jarnhammar A, Widell KO, Jernberg P, Jansson G, Zackrisson M, Holmer O (1999) Livscykelanalys av Färg. Livscykelanalys av färger för andvändning inom områdena industriell behandling av trä, industriell behandling av metal och måleri (*Life Cycle Assessment of Paint. Life cycle assessment of paints for use in industrial treatment of wood, industrial treatment of metal and paintings.*) Stockholm, IVL Report B 1338-A (in Swedish).

Bunke D, Gensch CO, Möller M, Rüdenauer I, Ebinger F, Graulich K (2003) Assessment of Toxicological Risks due to Hazardous Substances: Scoring of Risk Phrases. Int J Life Cycle Assess 8(1):6-7

Bunke D, Oldenburg C (2005) Indicators for Chemicals: Sources, impacts and policy performance. Environ. Sci. and Pollut. Res. 12(5):310-314

Commission of the European Communities (2007) Regulation (EC) No 1907/2006 of the European Parliament and of the council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC and 2000/21/EC. Off J Eur Union L 136 of

29.5.2007. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:136:0003:0280:EN:PDF

Commission of the European Communities (2008) Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (1).
Off J Eur Union L 353, Volume 51, 31 December 2008.P 1-1355.
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:353:0001:1355:EN:PDF

Council Directive 67/548/EEC of 27 June 1967 on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous components, Off J Eur Union L, 16.08.1967, 0001 – 0098.
http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexapi!prod!CELEXnumdoc&lg=EN&numdoc=31967L0548&model=guichett

Directive 1999/45/EC of the European Parliament and of the Council of 31 May 1999 concerning the approximation of the laws, regulations and administrative provisions of the Member States relating to the classification, packaging and labelling of dangerous preparations. Off J Eur Union L 200 , 30.07.1999, 0001 – 0068.
http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexapi!prod!CELEXnumdoc&lg=en&numdoc=31999L0045&model=guichett

ECHA (2008) Guidance on information requirements and chemical safety assessment. Part E: Risk Characterisation.
http://guidance.echa.europa.eu/docs/guidance_document/information_requirements_part_e_en.pdf?vers=20_08_08. Accessed 27 December 2010.

ECHA (2009) Introductory Guidance on the CLP Regulation.
http://guidance.echa.europa.eu/docs/guidance_document/clp_introductory_en.pdf. Accessed 6 June 2011.

Giudice F, La Rosa G, Risitano A (eds) (2006) Product Design for Environment – A Life Cycle Approach. Taylor and Frances, New York

Landsiedel R, Saling P (2002) Assessment of Toxicological Risks for Life Cycle Assessment and Eco-efficiency Analysis. Int J Life Cycle Assess 7(5):261-268

Mattila T, Verta M, Seppälä (2011) Comparing Priority setting in integrated hazardous substance assessment and in life cycle impact assessment. Int J Life Cycle Assess DOI: 10.1007/s11367-011-0295-5

Olsen SI, Christensen FM, Hauschild M, Pedersen F, Larsen HF, Tørsløv J (2001) Life cycle impact assessment and risk assessment – a methodological comparison, Environ Impact Assess Rev 21:385-404

Pant R, Van Hoof G, Schowanek D, Feijtel TCJ, de Koning A, Hauschild M, Pennington D, Olsen S, Rosenbaum R (2004) Comparison between Three Different LCIA Methods for Aquatic

Ecotoxicity and Product Environmental Risk Assessment. Insights from a Detergent Case Study within OMNITOX. Int J Life Cycle Assess 9(5):295-306

Potting J, Hauschild M, Wenzel H (1999) “Less is Better” and “Only Above Threshold”: Two Incompatible Paradigms for Human Toxicity in Life Cycle Assessment. Int J Life Cycle Assess 4(1):16-24

PRé Consultants (2011) SimaPro 7.3.0 Amersfoort, The Netherlands, www.pre.nl

Rønning AR, Hanssen OJ, Møller H (1995) Environmentally Sound Product Development of Offshore Coatings), Ostfold Research, Norway, OR 40.95

Saling P, Kicherer A, Dittrich-Krämer B, Wittlinger R, Zombik W, Schmidt I, Schrott W, Schmidt S (2002) Eco-Efficiency Analysis by BASF: The Method. Int J Life Cycle Assess 7(4):203-218

Saling P, Maisch R, Silvani M, König N (2005) Assessing the Environmental-Hazard Potential for Life Cycle Assessment, Eco-efficiency and SEEBalance®. Int J Life Cycle Assess 10(5):364-371

Udo de Haes HA, Finnveden G, Goedkoop M, Hauschild M, Hertwich EG, Hofstetter P, Jolliet O, Klöppfer W, Krewitt W, Lindeijer E., Müller-Wenk R, Olsen SI, Pennington DW, Potting J, Steen B (2002) Life Cycle Impact Assessment: Striving Torwards Best Practice. Society of Environmental Toxicology and Chemistry. SETAC Press, Penascola Fl, USA

UN GHS (2005) Globally Harmonized System of Classification and Labelling of Chemicals (GHS) http://www.unece.org/trans/danger/publi/ghs/ghs_rev01/01files_e.html. Accessed 1st April 2011

Van Leeuwen CJ, Vermeire TG (eds.) (2007) Risk Assessment of Chemicals: An Introduction, 511-551. Springer, The Netherlands

Strategy Tool Trial for Office Furniture

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Abstract

Purpose
A strategic product development tool combining REACH, environmental and financial factors was previously developed for a coatings company. This paper presents results from refining this tool for an office furniture company, using LCA-based environmental information, addressing the research questions:

- Is it possible to combine information from REACH with the LCA approach to provide useful information for a furniture producer in their environmental product development process?
- Does the approach developed for substances in mixtures need to be adapted for articles?
- Is there a correlation between energy consumption and the environmental impacts analysed?
- Will product designers get the same information independent of the environmental impact category used?
  - Will the strategy tool indicate the same ranking of products for all environmental impacts?
  - Does REACH information indicate the same set of priorities as those arising from LCA environmental data alone? (Do they agree, or is there a conflict?)
- Will strategic decisions differ if different environmental indicators are in focus?

The Strategy Tool's purpose is to analyse company product portfolios, identifying products that need redevelopment or redesign because of issues concerning hazardous substances, or environmental performance.

Methods
The LCA data used is cradle-to-gate data from Type III Environmental Declarations for 11 seating solutions. REACH Complexity, health hazard and environmental class indicators (based on risk phrases) are combined with financial data and LCA-based indicators. The correlation between energy consumption data and environmental impact results is analysed.

Results
Correlations between energy consumption and the environmental impacts global warming, acidification, eutrophication and heavy metals are presented. Strategy Tool figures are shown for

energy consumption, ozone depletion potential and photochemical oxidation potential. The results for office chairs and conference/visitor chairs are presented separately, as the two types of chairs fulfil different functions.

Conclusions
The correlation between energy consumption and certain environmental impact indicators affords a simplification of the product development process, since energy consumption can be used as a reasonable proxy for these indicators. The results support acknowledged principles of Ecodesign. Energy and materials minimization improves environmental performance - higher recycled material content and proportion of renewable energy resources are also beneficial. Designers have to consider multiple aspects in parallel and the Strategy Tool is useful for this purpose; the furniture producer has gained useful product development insight. The tool is applicable for strategic choice of products for development or redesign, that can be useful across many business sectors.

Keywords: REACH, Strategic decision-making, sustainable product development, health hazard, environmental hazard, furniture

1 Introduction

A Strategy Tool was developed for a coatings company as part of the Innochem project (Innovations in response to new regulations of conventional materials in a life cycle, functional and holistic perspective) (Hanssen 2010). Innochem was conceived as a result of the challenges facing companies in Europe as a result of the adoption of the REACH directive (Registration, Evaluation, Authorisation and Restriction of Chemicals, Commission of the European Communities 2007). Innochem is a collaborative project involving companies (Jotun and HÅG) and research institutions (Ostfold Research, NIVA, University of Oslo and Aalborg University) financed by the Norwegian Research Council, the Confederation of Norwegian Enterprise and participating companies. Jotun is a coatings production company and HÅG is part of Scandinavian Business Seating, producing chairs for the office and conference environment. A coatings company produces products that are mixtures of substances, as defined in REACH. The work presented in this paper tested the application to articles of the Strategy Tool developed for substances in mixtures. An article is defined as “an object which during production is given a special shape, surface or design which determines its function to a greater degree than does its chemical composition” (Commission of the European Communities 2007). This was done in order to answer the following research questions:

- Is it possible to combine information from REACH with the LCA approach to provide useful information for HÅG in their environmental product development process?
- How does the approach developed for a chemical mixtures producer need to be adapted for an article producer such as HÅG?

HÅG’s interest in the Strategy Tool and their efforts to document the life cycle environmental impacts of their products are a consequence of their rigorous environmental policy (HÅG 2010), which requires that they produce chairs with a long life, that are made of durable and “environmentally friendly materials”. Other activities in the Innochem project involving HÅG have focussed on using this LCA-based information for Ecodesign purposes. Thus it was also of interest to answer the following research questions:

- Is there a correlation between energy consumption and the environmental impacts analysed?
- Will product designers get the same information independent of the environmental impact category used?
  - Will the strategy tool indicate the same ranking of products for all environmental impacts?
  - Does REACH information indicate the same set of priorities as those arising from LCA environmental data alone? (Do they agree, or is there a conflict?)
- Will strategic decisions differ if different environmental indicators are in focus?

2 Methods

The methodological basis for the strategy tool presented in this paper is in a similar form to the Eco-portfolio matrix presented by Brezet et al. (1997), and the portfolio strategy matrix (Hedley in De Wit and Meyer, 2004); both of which were inspired by the Boston Consulting Group's general Growth-Share Matrix (Kotler in Brezet et al. 1997). In the Eco-portfolio matrix, the y-axis is a scale of potential environmental merit, while the x-axis represents market potential. The Strategy Tool presented in Askham et al. (2011) contains more complex environmental information, with each axis representing product qualities; the y-axis (VOC concentration) is one indicator of environmental quality, while the x-axis represents an indicator incorporating three different REACH aspects. REACH Complexity and health / environmental risk indicators are combined to make the index represented along the x-axis, called Total REACH, Health and Environmental Score. Table 1 gives a summary of the indicators used and how they were combined in the Strategy Tool for the coatings company and their offshore products range. Financial information (annual turnover for the specific products) has been incorporated in the size of the spheres presented in the figures presented in this paper. The Strategy Tool presents a more complex picture than the Eco-portfolio matrix, incorporating several environmental quality indicators into the tool.

The focus of this paper is to build on the original outline of the Strategy Tool (Askham et al. 2011) by presenting and discussing results from further testing of the tool in a different business sector (furniture). In addition the environmental merit scale is also examined in further detail. Here the data used for environmental merit is based on LCA results from existing environmental product declarations (EPDs) that the furniture-producing company has commissioned and published through the Norwegian EPD programme (EPD Norge 2011a). The LCA approach used for the EPD work can be described as retrospective (Tillmann 2000, Ekvall et al. 2005), or attributional (European Commission 2010), and this is appropriate for Type III Environmental Declarations and Ecodesign projects (Baumann and Tillmann 2004, European Commission 2010). The methodological basis for calculation of the impacts included in the seating solution EPD are documented in Nereng and Modahl (2007 and 2008) and Nereng (2009), and have been verified according to the Norwegian EPD system requirements. More details on the specific system boundaries and calculations on which each EPD is based can be found in the relevant EPDs from 2007-2009 (EPD Norge 2011b, EPD H03 320, 2007; EPD H04 4400, 2007; EPD H05 5300, 2007; EPD Capisco 8106, 2007; EPD H09 9230, 2007; EPD H04 4470, 2007; EPD H05 5370, 2007; EPD Futu, 2009; EPD Sideways 9732, 2008; EPD Conventio Wing 9811, 2008; EPD Conventio 9510, 2007). The term energy consumption, as used throughout this paper, is the term used in the EPDs (The Norwegian EPD Foundation 2008). This is primary energy consumption for energy carriers consumed over the whole product life cycle, measured in MJ units (in line with recommendations in European Commission 2010b); it does not include energy resources that are feedstocks for materials (for example crude oil as a feedstock for plastics production).

Table 1: Strategy Tool matrix developed for coatings, used as the basis for the office furniture test (based on Askham et al. 2011).

<table>
<tr><th>Axis</th><th>Comment</th><th>Indicator</th><th>Definition</th></tr>
<tr><td rowspan="3">x-axis: Total REACH, Health and Environmental Score</td><td rowspan="3">The sum of the indicators REACH Complexity, Health Hazard Class and Environmental Hazard Class.</td><td>REACH Complexity</td><td>The number of exposure scenarios required for the product (Article 14, Commission of the European Communities 2007), scores assigned: 0 exposure scenarios = 0; 1-2 exposure scenarios = 1; 3-5 exposure scenarios = 5; more than 5 exposure scenarios =10.</td></tr>
<tr><td>Health Hazard Class</td><td rowspan="2">Based upon the risk phrases (R-phrases) for effects on human health and the environment associated with chemicals in line with European hazard labelling directives (Council Directive 67/548/EEC, Directive 1999/45/EC). The R-phrases are grouped into three risk categories: low, medium and high. Table E.3-1 REACH CSA guidance (ECHA 2008) and COSHH (HSE1999). The R-phrases hazard level classifications are weighted: low, medium and high hazard levels are assigned the values 1, 3 and 10 respectively (based on expert judgement at Jotun).</td></tr>
<tr><td>Environmental Class</td></tr>
<tr><td>y-axis: Environmental Merit</td><td>Specifically relevant for paints products</td><td>VOC concenetration</td><td>g/l VOC concentration in the product, shown in relation to a relevant VOC limit (Ökopol 2009).</td></tr>
</table>

The emissions contributing to several of the environmental impact categories can be associated with fossil-based energy carrier consumption. There is also literature supporting the use of energy consumption as an indicator for the environmental performance of products (for example Huijbregts et al. 2006). If there is a strong correlation between energy consumption and other environmental impacts, it affords a potential simplification of the product development process, since energy consumption might then be used as a reasonable proxy for each of the indicators with which it correlates. In order to begin answering the research questions, correlations between the energy consumption data and a number of other environmental impact results from the EPDs were examined. Linear regression analysis was performed; using a linear least squares fit for the linear relationships shown in Figure 1. This analysis was performed in Excel and the correlation coefficient (R^2) values are shown for the trend lines. This is in line with the approach used by Huijbregts et al. (2006) and Capello et al. (2008).

The environmental data from EPDs for eleven of HÅG’s seating products was used to provide empirical data to test in the new business environment the Strategy Tool originally developed for mixtures of substances. The results from entering HÅG’s product data into the Strategy Tool are presented in Figures 2-7. These figures show how the Strategy Tool results differ with differing indicators of environmental quality (y-axis).

3 Results

3.1 Correlations between Environmental Indicators

The environmental impact results from the EPDs for the 11 seating solutions are presented in Table 2. It is often assumed that several environmental impacts are related to energy consumption. In order to answer the research question "Is there a correlation between energy consumption and the environmental impacts analysed?", potential correlations between the different environmental impact data were examined. Figure 1 shows the correlation of several potential impacts (global warming, eutrophication, acidification and heavy metals) with the energy consumption data from the seating solution EPDs. The environmental indicator data in Table 1 shows that the different environmental impacts have different orders of magnitude. In order to present these impacts in the same figure, the data in Table 1 (apart from global warming) were scaled, by multiplying by a scaling factor as shown in the legend of Figure 1. The correlations remain unchanged by this scaling. The scaling factors are shown in the legend in Figure 1. Figure 1 shows that these impacts have a strong correlation to energy consumption. The data for the other impact categories (ozone depletion and photochemical ozone creation potential) did not show any significant correlation with energy consumption, or with each other.

Table 2: EPD data for 11 HÅG Seating Solutions.

Seating Solution	Office/ Conf./ Visit.	Energy Cons-ump-tion (MJ)	Global warm-ing poten-tial (kg CO2-equ.)	Acid-ifica-tion poten-tial (g SO2-equ.)	Photo-chemical oxidation potential (g ethane-equ.)	Eutro-phication potential (g phos-phate -equ.)	Ozone depletion potential, (mg CFC-11 equ.)	Heavy metals EI 95 (mg Pb equ.)
		/seating solution						
Product 1	Office	829	45	0.18	0.038	0.031	3.1 E-05	6.2 E-04
Product 2	Office	1257	63	0.28	0.035	0.043	2.4 E-06	1.1 E-03
Product 3	Office	1050	57	0.24	0.026	0.036	1.6 E-05	8.9 E-04
Product 4	Office	807	38	0.16	0.039	0.027	5.8 E-05	5.6 E-04
Product 5	Office	1518	68	0.35	0.064	0.044	3.7 E-05	9.0 E-04
Product 6	Office	1072	55	0.24	0.049	0.037	5.5 E-05	7.1 E-04
Product 7	Conf. /visitor	691	41	0.16	0.032	0.025	2.1 E-05	2.3 E-04
Product 8	Conf. /visitor	555	30	0.13	0.025	0.017	4.6 E-05	1.3 E-04
Product 9	Conf. /visitor	397	24	0.10	0.020	0.013	3.1 E-05	1.3 E-04
Product 10	Conf. /visitor	629	31	0.12	0.036	0.019	7.5 E-05	3.1 E-04
Product 11	Conf. /visitor	952	56	0.24	0.046	0.040	2.8 E-06	7.1 E-04

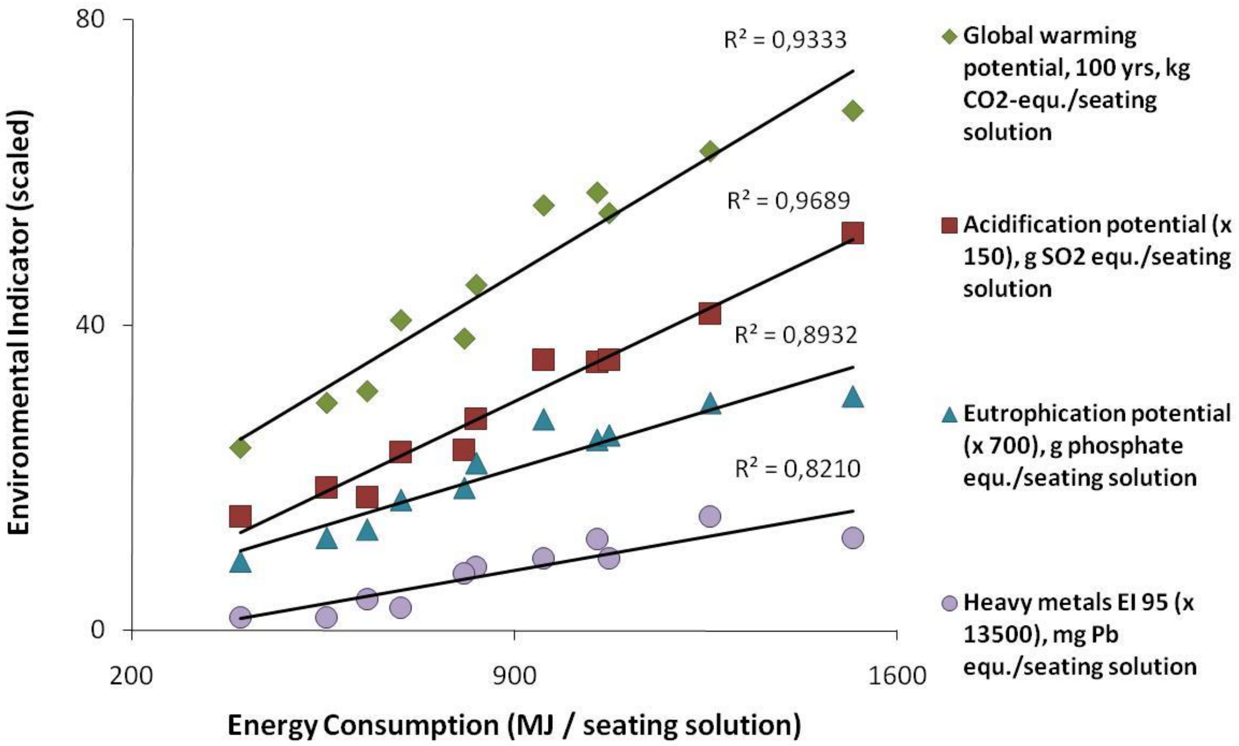

Fig. 1 *Correlations between energy consumption and potential environmental impacts: global warming, eutrophication, acidification and heavy metals.*

The presence of the strong correlations between results for the environmental indicators energy consumption, global warming, eutrophication, acidification and heavy metals mean that the ranking of products will be similar for these indicators. The research question "Is there a correlation between energy consumption and the environmental impacts analysed?", is answered partly in the affirmative. Energy consumption correlates strongly with the indicators shown in Figure 1 and weakly (or not at all) with the others - namely, ozone depletion and photochemical ozone creation potential. The next stage is to investigate the research questions regarding the ranking of products. Since energy consumption can be used as a proxy for eutrophication, acidification or heavy metals, it is only necessary to consider one of these four indicators (energy consumption) in the following analysis, alongside the indicators with which energy consumption does not correlate. Ranking of products is investigated by considering their Total REACH, Health and Environment Score in relation to the various environmental indicators.

Figures 2-7 show results from the Strategy Tool for 11 seating solutions in HÅG's product range. Products 1-6 (figures 2, 4 and 6) are office chairs, and products 7-11 (figures 3, 5 and 7) are visitor or conference chairs. The size of the spheres shown in figures 2-7 represent the total sales volumes for these products in 2010 (Aaser 2011). Figure 2 shows that the office chair with the largest sales volume (Product 4) has the smallest energy consumption. Products 1 and 4 have the smallest energy consumption and products 5 and 2 the largest.

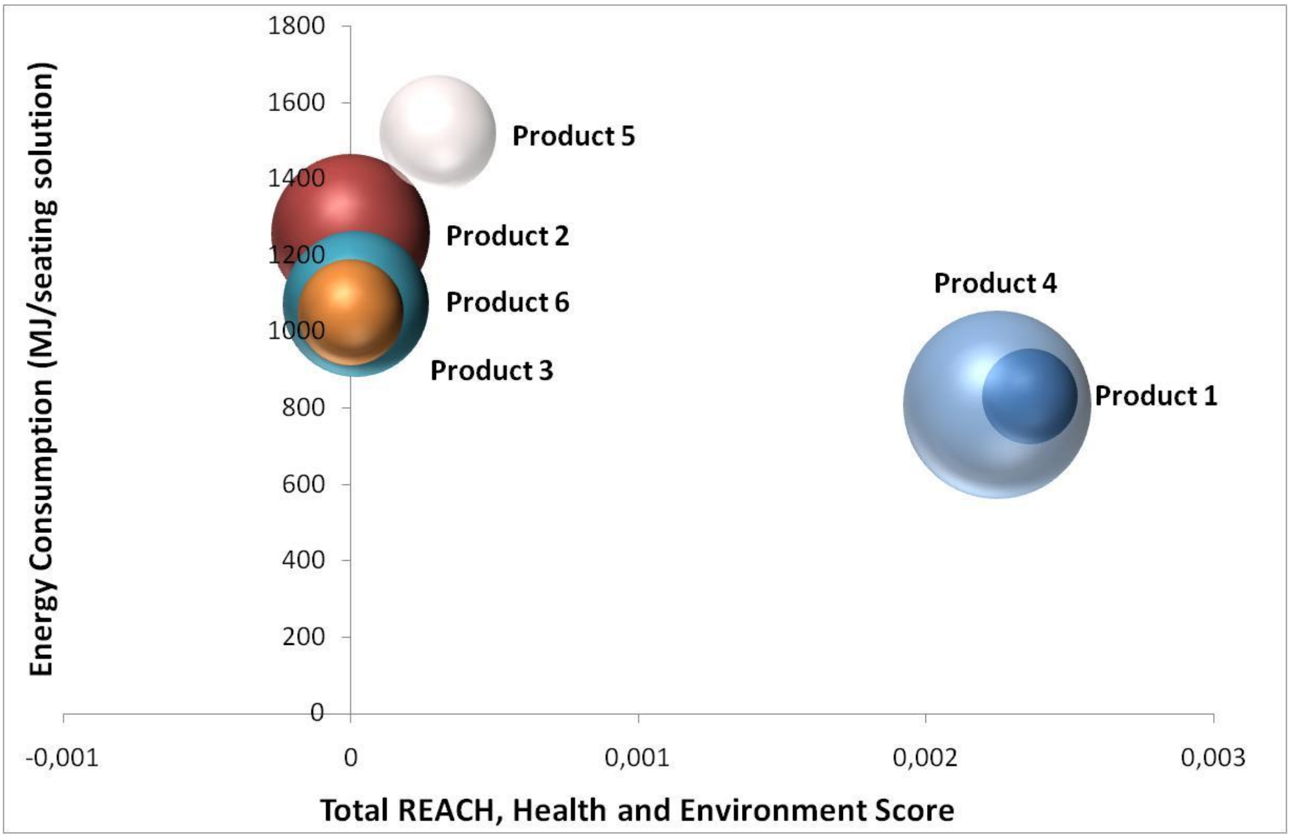

Fig. 2 *Strategy Tool Results for Office Chair Products; Environmental quality scale - Energy Consumption.*

Figure 2 shows that products 1, 4 and 5 all have a Total REACH, Health and Environment Score greater than zero. The reason for this is that these products contain a raw material (loctite) that has a hazard labelling requirement according to European hazard labelling directives (Council Directive 67/548/EEC, Directive 1999/45/EC). The amount of loctite used varies between the products, but is small in all cases. Furthermore, before the products reach the customer, the loctite glue has cured into an inert form, meaning that labelling of these products is not required.

When examining the LCA models on which the EPDs were based (Nereng and Modahl 2007, Nereng and Modahl 2008, Nereng 2009), it was found that energy consumption was largely attributable to the energy consumed in the value chains for metal components. Lower energy consumption is achieved for lightweight models with lower material consumption, also for models with higher recycled raw material content. Fossil energy carriers dominate energy consumption in the value chains for all of the chair models.

Figure 3 shows that the two visitor and conference products with the largest sales volumes are those with the smallest energy consumption. Product 11 has the largest energy consumption of the visitor and conference products. Figure 3 shows that none of these products contain components or substances that have a labelling requirement. Comparing figures 2 and 3, visitor and conference chairs have a lower energy consumption than office chairs. This is due to their lower material consumption.

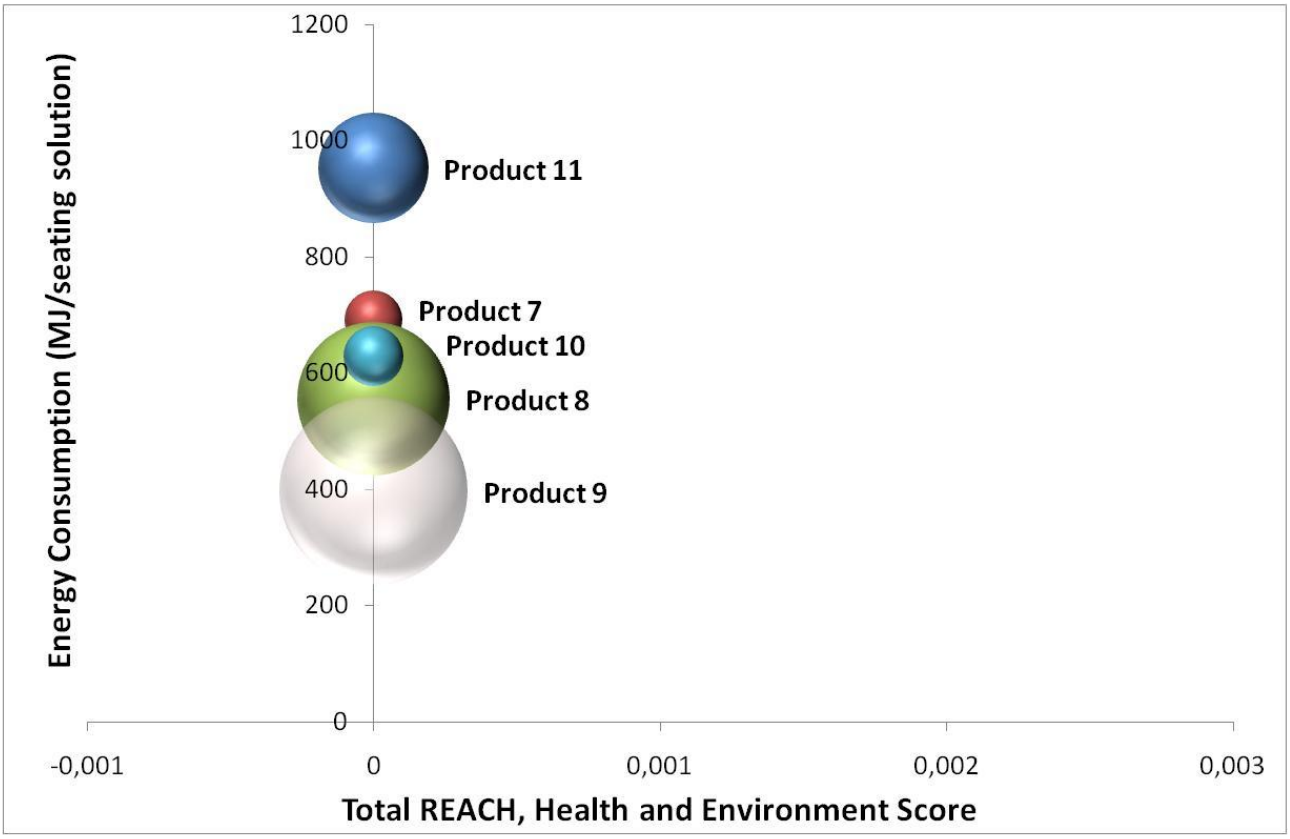

Fig. 3 *Strategy Tool Results for Visitor and Conference Products; Environmental quality scale - Energy Consumption.*

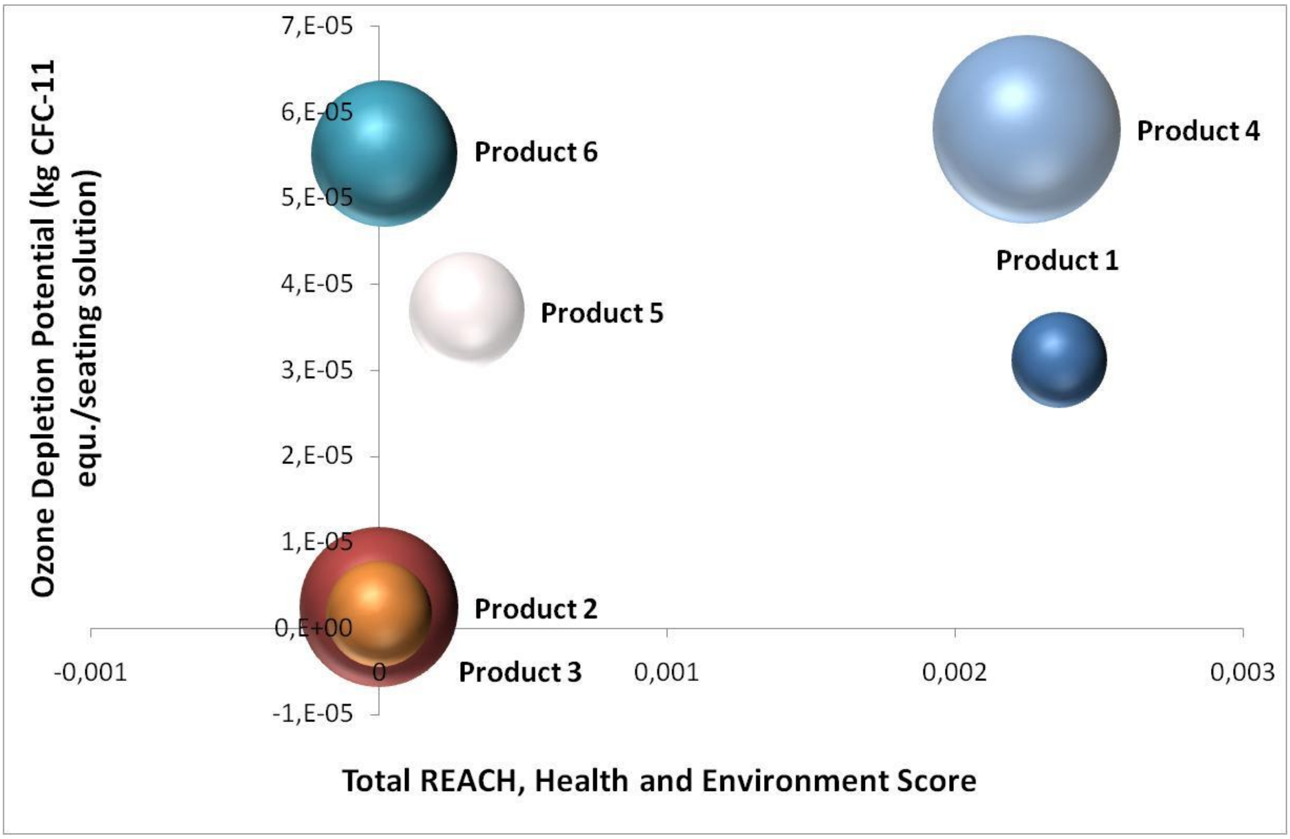

Fig. 4 *Strategy Tool Results for Office Chair Products; Environmental quality scale - Ozone Depletion Potential.*

Figures 4-7 show the Total REACH, Health and Environmental Score for the products as in figures 2 and 3, but with different environmental merit axes. Figures 4 and 5 show ozone depletion potential (ODP) , and figures 6 and 7 show photochemical oxidation (PCOP).

The office chair results in Figure 4 show that Product 4 has the largest ODP and sales volume, and one of the largest Total REACH, Health and Environmental Scores. Products 4 and 6 are the office chairs with the largest ODP, and Products 2 and 3 have the smallest. The visitor and conference chair results shown in Figure 5 show that Products 8 and 10 have the largest ODP, while Products 7 and 11 have the smallest.

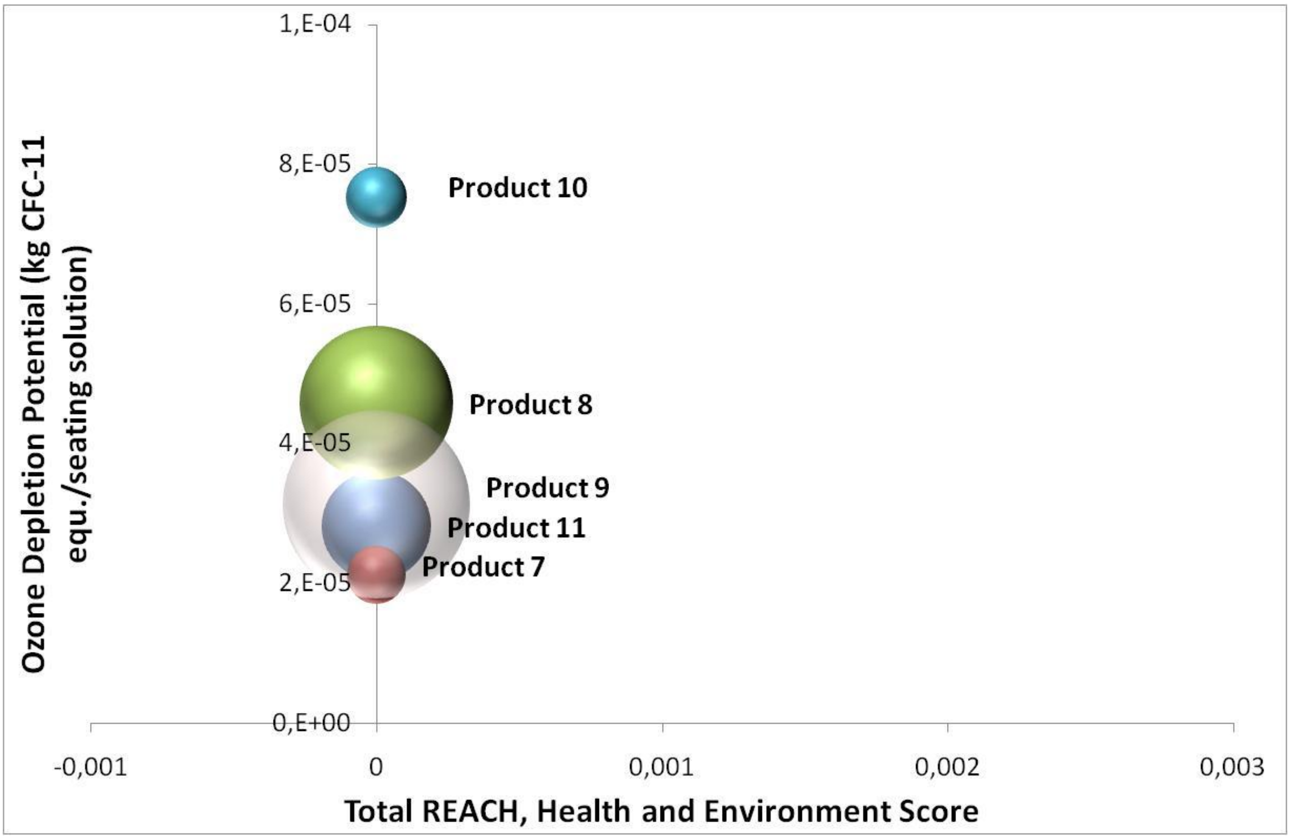

Fig. 5 *Strategy Tool Results for Visitor and Conference Products; Environmental quality scale - Ozone Depletion Potential.*

ODP largely arises from refrigerants and fire suppressants / flame retardants; the refrigerants are attributable to nuclear power in the electricity mixes used, and the flame suppressants used in the offshore and onshore oil and gas sector. Product 10 is a chair with a relatively high proportion of polypropylene plastic content, while Product 7 contains aluminium with a high recycled content.

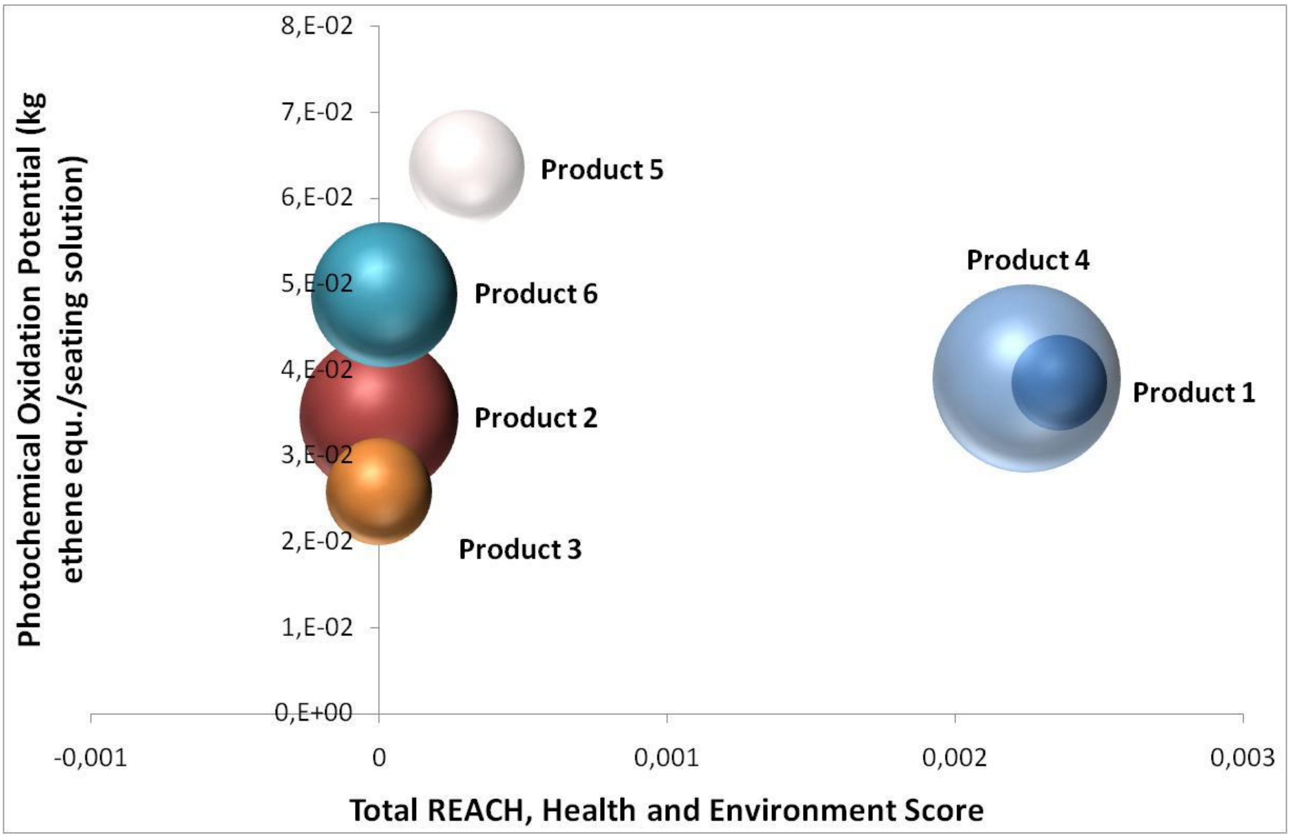

Fig. 6 *Strategy Tool Results for Office Chair Products; Environmental quality scale - Photochemical Oxidation Potential (PCOP).*

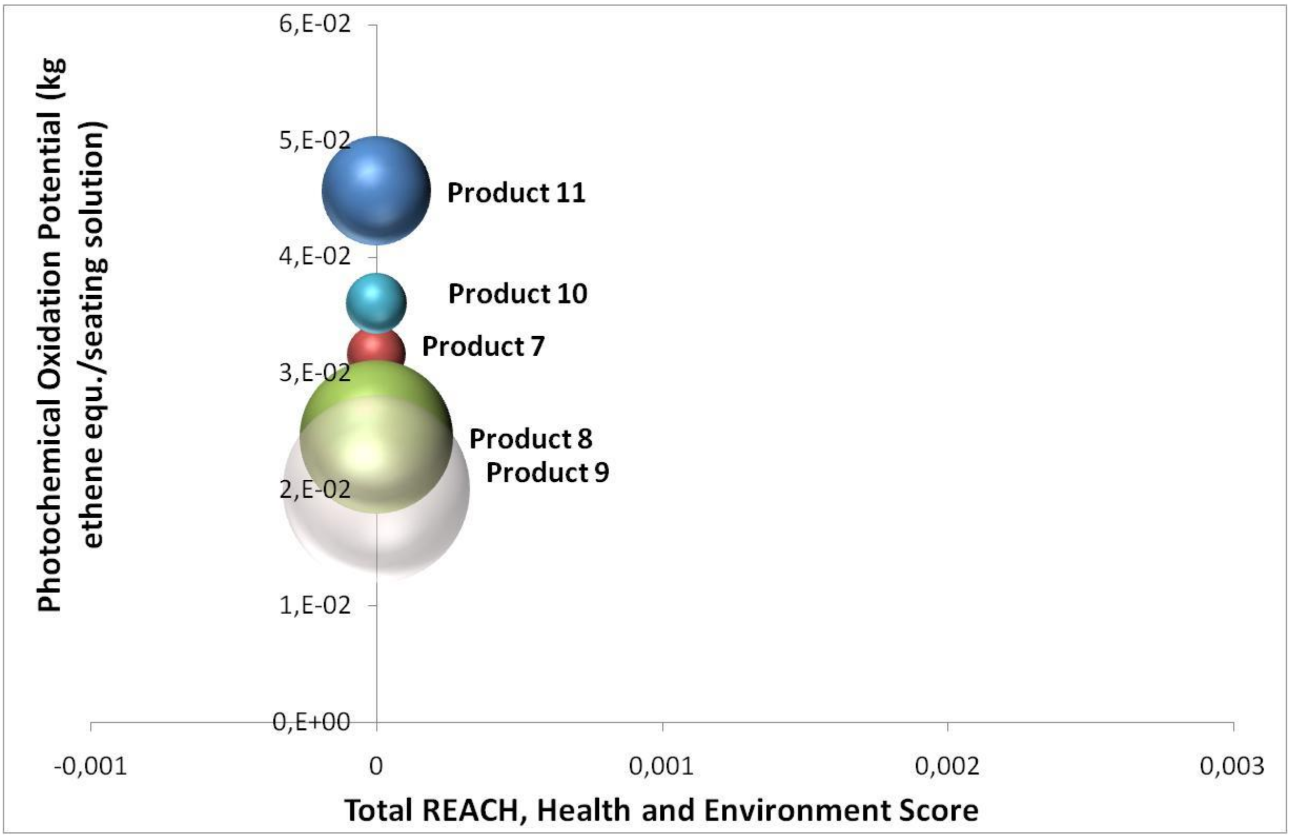

Fig. 7 *Strategy Tool Results for Visitor and Conference Products; Environmental quality scale - Photochemical Oxidation Potential (PCOP).*

Figure 6 shows that products 5 and 6 are the office chairs with the largest PCOP, whereas products 2 and 3 have the smallest. Figure 7 shows that products 10 and 11 are the conference/visitor chairs with the largest PCOP, whereas 8 and 9 have the smallest. Emissions of non-methane volatile organic compounds (NMVOCs) is the main cause of POCP. Carbon monoxide and nitrous oxide emissions are also significant. Sulphur oxide emissions are only significant for two of the conference/visitor products (3 and 8), which have relatively high polyamide content; however figures 6 and 7 show that these products perform relatively well overall in terms of POCP. NMVOC emissions arising from production of metals are mainly responsible for the POCP levels for the chairs with the worst POCP performance (both office and conference/visitor models, products 5 and 11).

Table 3 summarises the results for product ranking from the Strategy Tool according to the different environmental impact indicators for the environmental merit axis (y-axis) and Total REACH, Health and Environment Score (x-axis).

Table 3: Product ranking from the Strategy Tool matrix indicators.

Axis	**Office Chair Products**		**Visit and Conference Products**	
	The best	The worst	The best	The worst
Environmental merit scale (y-axis)				
Energy Consumption	1 and 4	2 and 5	8 and 9	7 and 11
Ozone Depletion Potential	2 and 3	4 and 6	7 and 11	8 and 10
Photochemical Oxidation Potential	2 and 3	5 and 6	8 and 9	10 and 11
Total REACH, Health and Environment Score (x-axis)	2, 3 and 6	1 and 4	All the same	

4 Discussion

The environmental impact results from the EPDs for the 11 seating solutions are presented in Table 2. It is a common assumption that several environmental impacts are related to energy consumption and several authors have identified cumulative energy demand as a useful indicator for the environmental performance of products (for example Capello et al. 2009, Huijbregts et al. 2006). In order to answer the research question “Is there a correlation between energy consumption and the environmental impacts analysed?”, potential correlations between the different environmental impact data were tested. The potential impacts global warming, eutrophication, acidification and heavy metals show a strong correlation with the energy consumption data from the seating solution EPDs. The data for the other impact categories (ozone depletion and photochemical ozone creation potential) did not show any significant correlation to energy consumption, or to each other. The summary of the product ranking results from the Strategy Tool test presented in Table 3 show that the choice of indicator for the environmental merit axis (y-axis) will be very significant for the results. This relates to the following research questions :

- Will product designers get the same information independent of the environmental impact category used?
  −Will the strategy tool indicate the same ranking of products for all environmental impacts?
  − Does REACH information indicate the same set of priorities as those arising from LCA environmental data alone? (Do they agree, or is there a conflict?)
- How will strategic decisions differ if different environmental indicators are in focus?

The results shown in Figure 1 and Table 3 show that it is not true that the Strategy Tool will indicate the same ranking of products for all environmental impacts.

The purpose of the Strategy Tool is to identify products that have the greatest need for further development, or re-design. Using the tool to analyse whether products in a product range have issues concerning hazardous substances and / or environmental performance that can become a problem in the future enables a company to target its product development resources efficiently. The results presented in this paper make it clear that HÅG’s products do not generally have any significant REACH issues (Total REACH Complexity, Health and Environmental Score of zero, or very low in Figures 2-7). This is an important result for HÅG, showing that they are unlikely to be significantly affected by REACH, a fact that can be used in communication with the market.

For producers of substances in mixtures, the Total REACH, Health and Environmental Score presented in Askham et al. (2011) was applicable to the mixture when threshold level values for component chemicals were exceeded. This was an example of data for “above threshold” situations typical for risk assessment (Potting et al. 1999). However, for HÅG’s products the amount of glue used was very small. It was nonetheless desirable to distinguish between the products that used small amounts of this raw material, from a “less is better” (Potting et al. 1999) standpoint. After in depth discussion in the project team, the tool was adapted to include the mass fraction for the labelled component in the required data. This enabled a more accurate calculation of the Total REACH, Health and Environment Score than if the quantitative mass fraction data were not included in the calculations. One result was that Products 1, 4 and 5 were distinguishable by this score where otherwise they would not have been. This adaptation has been tested here and has also been adopted by the coatings company in further work. In considering the research question "does the approach developed for substances in mixtures need to be adapted for articles?", it is apparent that the Strategy Tool as presented in this paper has been useful in both business environments. Thus, the conclusion is that no significant adaptation is necessary.

The discussion process (leading to the mass fraction adaptation described above) yielded a proposal to include limit values for chemicals in order to differentiate between products. The limit values proposed were threshold limit values for classification of both human health and environmental hazards based on legal requirements for substance and product classification and labelling in Europe (Council Directive 67/548/EEC, Directive 1999/45/EC).When comparing product development processes in article producers with those for substance / mixture producers, it should be noted that both the available information and the technical competence differs considerably. An article producer buying component parts, glues and lubricants and obtaining safety data sheets (SDSs) for these (often multi-component parts, or mixtures of chemicals) will more readily fill out risk phrases that are in SDSs for the raw material, rather than enter specific chemical compositions from SDSs. Regarding the loctite glue component responsible for the hazard level shown, it is likely that article producers can readily determine the mass of a given raw material and its hazard rating from the SDS. In contrast, the limit values for hazard labelling, such as are used by producers of chemical mixtures, will not be readily available from SDSs. The specific loctite SDS available to HÅG during the Strategy Tool test (Reyher 2010) did not contain this threshold limit value information. Thus the mass ratio and risk level were combined, without relating them to the limit values for the relevant component chemicals in loctite. No general survey about whether or not this is a genuine difference in the needs for producers of substances in mixtures and article producers has been performed. However, this is could be explored further in future work.

There are some general trends for Ecodesign that arise from the LCA results (the environmental merit axes in figures 2-7). These indicate that low material consumption and low energy consumption is preferable. Models using a high proportion of recycled materials are also preferable. Lower consumption of fossil fuels for both energy and materials gives a lower score for all of the environmental indicators used. ODP results indicate that renewable energy sources are preferable. This is also supported by a recent European Environment Agency (EEA) report, which shows signs of the decoupling of economic activity with environmental impacts (although it should be noted that this report focuses mainly on greenhouse gas emissions, EEA 2011). This report finds that an increase in the use of renewable energy sources is a significant contributor to this decoupling, although decreased economic activity, as a result of economic recession is the most significant cause of European emissions reductions. All of these Ecodesign trends are in line with general Ecodesign principles that have been published by other authors (for example Brezet et al. 1997).

HÅG has used the results of this Strategy Tool work as input into their company strategy and product development work. HÅG's focus on being at the forefront of Ecodesign based on LCA has resulted in the products that have the largest turnover also being those with the lowest energy consumption and global warming potential. Another interesting observation is that Product 4 is a flagship product with high turnover. Thus it is of interest to reduce all of the impact indicators to as close to zero as possible, this product will be prioritised for Ecodesign efforts in order to remove the Total REACH, Health and Environmental Score and reduce the other environmental impact indicators as far as possible. Product 1 is an old product in their range, which will not be prioritised for further development. The efficient identification of relevant products for further development or redesign is an example of how using the Strategy Tool has enabled important improvements to the company's product development process. This can thus lead to considerable improvements in the company's overall environmental performance.

HÅG's experience is that their customers are mostly interested in carbon footprint at the present time. In figures 2 and 3 the chairs with the largest sales volumes have the lowest energy consumption. This can indicate that HÅG's focus on reduction of their carbon footprint has had some success. They have had focus on this issue in their product and supplier development work, and also in their marketing efforts. However, HÅG is also aware that there is increasing focus on other environmental aspects and have identified chemicals in products and chemical hazard as important for the future. As a consequence of this HÅG has obtained the GREENGUARD certification (Greenguard 2011) for all of their products that have EPDs. Use of the Strategy Tool has enabled HÅG to identify three products in their range that contain a raw material with a labelling requirement, resulting in implications for the workplace environment at HÅG's production facility. From this work, HÅG has identified the relevant raw material and has challenged its product designers to seek alternative solutions. The loctite glue is used to secure screws firmly in place throughout the entire guaranteed product lifetime. Alternative designs of the relevant parts are now being investigated, such as those involving mechanical solutions, namely washers that lock the screws into place.

Figures 2-7 illustrate the use of the Strategy tool to combine REACH Complexity, health hazard class, environmental class and environmental merit indicators in order to provide information about several aspects at once for company strategy and product design. This has in turn been used to identify one (small) area for redesign that applies to several products. This indicates an affirmative answer to the research question "Is it possible to combine information from REACH with the LCA approach to provide useful information for a furniture producer in their environmental product development process?"

One research question that has not yet been specifically addressed in this discussion is: "Does REACH information indicate the same set of priorities as those arising from LCA environmental data alone? (Do they agree, or is there a conflict?)" The visitor and conference products are not distinguishable by REACH Complexity, Health and Environmental Score (it is zero in all cases), thus there is no effective conflict in priorities for these products – priorities relate solely to LCA environmental indicators. Table 3 summarises the product rankings for the environmental indicators and the Total REACH, Health and Environment Score. Products 2, 3 and 6 come out best for the axis where REACH and chemical hazard information is in focus; these clearly differ from the best-ranked products with respect to energy consumption. In addition, Product 6 is also ranked as one of the worst for ozone depletion potential and photochemical oxidation potential. Thus, at least in some cases there is a marked conflict in priorities. This suggests that, in general, product development should encompass both REACH information and LCA data, so as to adopt a balanced view on environmental performance factors. Trade-offs will often need to be considered; use of the Strategy Tool brings such trade-offs into clear focus and thus offers important information to the product developer.

The strategic product development decisions informed by the Strategy Tool concern which products are important for development and redesign efforts to improve the environmental performance of a product portfolio, as well as reduce REACH Complexity and health and environmental hazards associated with the product and its raw materials. The difference in ranking of products described above, indicates that the answer to the final research question “Will strategic decisions differ if different environmental indicators are in focus?” is affirmative. Different products are likely to be focussed upon if different indicators are used as a basis for the decision. However, the Strategy Tool test for HÅG has also identified qualitatively different challenges for different products. HÅG has now a greater awareness of these different challenges and can combine this with other information (for example what their customers and stakeholders are concerned about) in order to make decisions about which products should be developed or redesigned. Such knowledge enables a proactive approach to stakeholder concerns.

5 Conclusions

The correlations between energy consumption and the potential environmental impact indicators global warming, acidification, eutrophication and heavy metals were sufficiently significant that energy consumption could be used as a reasonable indicator for all of these impacts. The Strategy Tool has been tested for 11 of HÅG’s products and has resulted in important input into strategic and product development decisions. The following research questions have been answered affirmatively by the work presented in this paper:

- Is it possible to combine information from REACH with the LCA approach to provide useful information for a furniture producer in their environmental product development process?
- Is there a correlation between energy consumption and the environmental impacts analysed?
- Will strategic decisions differ if different environmental indicators are in focus?

The work presented has also provided evidence that the answers to the following research questions are negative:

- Will product designers get the same information independent of the environmental impact category used?
  - Will the strategy tool indicate the same ranking of products for all environmental impacts?
  - Does REACH information indicate the same set of priorities as those arising from LCA environmental data alone? (Do they agree, or is there a conflict?)
- Does the approach developed for substances in mixtures need to be adapted articles?

This testing of the Strategy Tool for articles, combined with the previous work presented in Askham et al. 2011 (using the tool for substances in mixtures) indicates that the tool can be useful both for substances in mixtures and articles. Thus it is a tool for strategic choice of products for development or redesign that can be useful across many business sectors.

Acknowledgements

The authors gratefully acknowledge the important contributions made by the companies participating in the Innochem project: Jotun AS and HÅG as, which have made this work possible, as well as the financial support provided by the Norwegian Research Council through the BIA program and the Confederation of Norwegian Enterprises through the Workplace Environment Fund. Thanks also to colleagues in Ostfold Research who have been important discussion partners during this work.

References

Aaser CP (2010) Personal communication, 10 January 2011.

Askham C, Gade AL, Hanssen OJ (2011) Combining REACH, Environmental and Economic Performance Indicators for Strategic Sustainable Product Development . Submitted to J. Cleaner Prod.

Baumann H, Tillman AM (2004) The Hitch Hiker's Guide to LCA, An orientation in life cycle assessment methodology and application, Studentlitteratur, Lund, Sweden.

Brezet H, van Hemel C (Ed.s) (1997) Ecodesign. A Promising Approach to Sustainable Production and Consumption. First Edition. United Nations Environment Programme, France.

Capello C, Wernet G, Sutter J, Hellwegg S, Hungerbühler (2009) A comprehensive environmental assessment of petrochemical solvent production. Int J Life Cycle Assess 14:467-479

CML (2010) CML-IA Characterisation Factors. http://cml.leiden.edu/software/data-cmlia.html. Accessed 27th May 2010.

Commission of the European Communities (2007) Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC and 2000/21/EC. Off J Eur Union L 136 of 29.5.2007.

Council Directive 67/548/EEC of 27 June 1967 on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous components. Off. J. Eur. Union L, 16.08.1967, 0001 – 0098.

Directive 1999/45/EC of the European Parliament and of the Council of 31 May 1999 concerning the approximation of the laws, regulations and administrative provisions of the Member States relating to the classification, packaging and labelling of dangerous preparations. Off. J. Eur. Union L 200 , 30.07.1999, 0001 – 0068.

ECHA (2008) Guidance on information requirements and chemical safety assessment. Part E: Risk Characterisation. http://guidance.echa.europa.eu/docs/guidance_document/information_requirements_part_e_en.pdf?vers=20_08_08. Accessed 27 December 2010.

EEA (2011) Annual European Union greenhouse gas inventory. 1990–2009 and inventory report 2011. Submission to the UNFCCC Secretariat. EEA Technical report No 2/2011. European Environment Agency, Copenhagen.

Ekvall, T, Tillmann, AM, Molander, S (2005) Normative ethics and methodology for life cycle assessment, J Clean Prod 13:1225-1234.

EPD Capisco 8106 (2007) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD038E%20Capisco%208106_English_2013.pdf. Accessed 30 March 2011

EPD Conventio 9510 (2007) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD042E%20Conventio%209510_English_2013.pdf. Accessed 30 March 2011

EPD Conventio Wing 9811 (2008) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD%20122E%20%20Conventio%20Wing%209811.pdf. Accessed 30 March 2011

EPD Futu (2009) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD075EA%20%20Futu_english_2014.pdf. Accessed 30 March 2011

EPD H03 320 (2007) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD034E%20H03%20320_English_2013.pdf. Accessed 30 March 2011

EPD H04 4400 (2007) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD035E%20H04%204400_English_2013.pdf. Accessed 30 March 2011

EPD H04 4470 (2007) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD040E%20H04%20Comm%204470_English_2013.pdf. Accessed 30 March 2011

EPD H05 5300 (2007) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD036E%20H05%205300_English_2013.pdf. Accessed 30 March 2011

EPD H05 5370 (2007) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD041E%20H05%20Communication%205370_English_2013.pdf. Accessed 30 March 2011

EPD H09 9230 (2007) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD039E%20H09%20Ins9230_English.pdf. Accessed 30 March 2011

EPD Sideways 9732 (2008) http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD%20121E%20Sideways%209732.pdf. Accessed 30 March 2011

EPD Norge (2011a) The Norwegian EPD Foundation. http://www.epd-norge.no/?lang=en_GB. Accessed 2 June 2011.

EPD Norge (2011b) EPD-registry Furniture. http://www.epd-norge.no/category.php?categoryID=435. Accessed 2 June 2011.

European Commission (2010a) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed Guidance. First edition 2010. EUR 24708 EN. European Commission, Joint Research Centre, Institute for Environment and Sustainability. Luxembourg. Publications Office of the European Union.

European Commission (2010b) International Reference Life Cycle Data System (ILCD) Handbook – Nomenclature and other conventions. First edition 2010. EUR 24384 EN. European Commission, Joint Research Centre, Institute for Environment and Sustainability. Luxemburg. Publications Office of the European Union.

Greenguard (2011) Greenguard Environmental Institute certificates for HÅGs products. http://www.greenguard.org/en/SearchResults.aspx?b=1,2,4&a=21|44|0|11|0|0|0|0|1|16|1&bs=Furniture|Seating|HAG. Accessed 21 June 2011.

Hanssen OJ (2010) Innochem, Ostfold Research. http://ostfoldforskning.no/Engelsk/prosjekt/innochem-448.aspx. Accessed 15 March 2010.

HSE (1999) COSHH essentials. Easy steps to control chemicals. Control of substances hazardous to health regulations. HSG193. HSE books, Surrey, UK.

Huijbregts MAJ, Rombouts LJA, Hellweg S, Frischnecht R, Hendriks Aj, Van De Meet D, Ragas AMJ, Reijnders L, Struijs J (2006) Is Cumulative fossil energy demand a useful indicator for the environmental performance of products? Environ Sci & Technology 40:641-648

HÅG (2009) Environmental Declaration HÅG H03 5300. http://www.epd-norge.no/getfile.php/PDF/EPD/Moebler/NEPD036Eng.pdf. Accessed 4th November 2010.

HÅG (2010) http://www.hag-uk.co.uk/about_hag/environment. Accessed 26 May 2010.

IPPC (2007) IPCC Fourth Assessment Report, IPCC 2007 GWP 100a V1.02, http://www.ipcc.ch/ipccreports/ar4-wg1.htm

Nereng G (2009) Livsløpsdata for sitteløsning fra HÅG. Bakgrunnsdata for miljødeklarasjon (EPD) av HÅG Futu (*Background data for environmental product declaration (EPD) of HÅG Futu)*, Ostfold Research, Norway, OR 14.09 (in Norwegian).

Nereng G, Modahl IS (2008) Livsløpsdata for sitteløsninger fra HÅG, HÅG Conventio Wing 9811 og HÅG Sideways 9832 (*Life cycle data for HÅG's seating solutions, HÅG Conventio Wing 9811 and HÅG Sideways 9832*), Ostfold Research, Norway, OR 18.08 (in Norwegian).

Nereng G, Modahl IS (2007) Livsløpsdata for sitteløsninger fra HÅG - Bakgrunnsdata for miljødeklarasjon (EPD) av seks sitteløsninger (*Life cycle data for HÅG's seating solutions – Background data for environmental product declaration (EPD) of six seating solutions*), Ostfold Research, Norway, OR 23.07 (in Norwegian).

Potting J, Hauschild M, Wenzel H (1999) “Less is Better” and “Only Above Threshold”: Two Incompatible Paradigms for Human Toxicity in Life Cycle Assessment. Int J Life Cycle Assess 4(1):16-24

Reyher (2010) http://www.reyher.de/download/Safety_Data_Sheet_Loctite_2701.pdf. Accessed 31 March 2011

Tillmann AM (2000) Significance of Decision-Making for LCA Methodology, Environ Impact Assess Rev 20:113-123.

The Norwegian EPD Foundation (2008) Product Category Rules for Preparing an Environmental Product Declaration (EPD) for Product Group Seating Solution, NPCR 0003, Revised version, October 2008.

Ökopol (2009) European Commission Service Contract N°070307/2007/483710/Mar/C3 Implementation And Review Of Directive 2004/42/Ec (European Directive Limiting The Voc Content In Certain Products – Current Scope: Decorative Paints And Varnishes, Vehicle Refinishing Products) Final Report (2 Parts) Part 1: Main Report, Annexes 1-25 10 November 2009. http://ec.europa.eu/environment/air/pollutants/pdf/paints_report.pdf